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Graphs, Formulas and Tables

relevant to

# *Transport Phenomena*

Martin Rohde



# Colophon

## Graphs, Formulas and Tables relevant to Transport Phenomena

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# Definitions

## Symbols used in this book

### Greek

$\alpha$	Linear thermal exp. coeff.	$m/(m.K)$
$\beta$	Cubic thermal exp. coeff.	$m^3/(m^3.K)$
$\gamma$	Solutal exp. coeff.	$m^3/kg$
$\eta$	Dynamic viscosity	$Pa.s$
$\nu$	Kinematic viscosity	$m^2/s$
$\rho$	Mass density	$kg/m^3$
$\lambda$	Heat conductivity	$W/(m.K)$
$\sigma$	Surface tension	$N/m$
$\tau$	Shear stress	$N/m^2$
$\phi_V$	Volumetric flow rate	$m^3/s$
$\phi_m$	Mass flow rate	$kg/s$
$\phi_q$	Heat flow rate	$J/s$
$\phi_W$	Work	$J/s$
$\phi_q''$	Heat flux	$W/m^2$
$\phi_m''$	Mass flux	$kg/(m^2.s)$

### Latin

$a$	Thermal diffusivity	$m^2/s$
$A$	Surface	$m^2$
$c$	Concentration	$kg/m^3$ $mol/m^3$
$C_D$	Drag coefficient	-
$C_p$	Specific heat capacity (at constant pressure)	$J/(kg.K)$
$D_h$	Hydraulic diameter	$m$
$e$	Specific energy	$J/kg$
$E$	Energy	$J$
$e_{fr}$	Energy dissipation	$J/kg$
$f$	Fanning friction factor	-
$F_b$	Buoyancy force	$N$
$F_D$	Drag force	$N$
$g$	Gravity constant	$m/s^2$
$F_g$	Gravitational force	$N$
$g$	Gravity constant	$m/s^2$
$h$	Heat transfer coeff.	$W/(m^2.K)$
$H$	Height	$m$
$H_s$	Henry's coefficient	$mol/(m^3.Pa)$

### Latin (cont'd)

$k$	Mass transfer coefficient	$m/s$
$k_r$	Reaction constant	reaction-specific
$K$	Overall mass transfer coeff.	$m/s$
$m$	Mass	$kg$
$m$	Partition coefficient	-
$M_w$	Molar weight	$g/mol$
$N$	Rotational rate	$s^{-1}$
$p$	Pressure	$Pa$
$P$	Power	$J/s$
$p_i$	Partial pressure of $i$	$Pa$
$Q$	Heat source	$J/s$
$R_A$	Reaction rate of A	$kg/s$ $mol/s$
$t$	Time	$s$
$T$	Temperature	$^{\circ}C, K$
$u$	Specific internal energy	$J/kg$
$U$	Overall heat transfer coeff.	$W/(m^2.K)$
$v$	Velocity	$m/s$
$V$	Volume	$m^3$
$x, y, z$	Cartesian coordinates	$m$
$x_i$	Mole fraction of $i$	-

### Other

$\mathbb{D}$	Diffusion coefficient	$m^2/s$
$\ell$	Characteristic length	$m$
$\langle \cdot \rangle$	Cross-sectional average	-

### Super/subscripts

'	Per $m$
"	Per $m^2$
'''	Per $m^3$

## Dimensionless numbers

$\ell$  = characteristic length scale of the problem, e.g. a diameter  $\ell = D$ .

symbol	name	definition	relates to
$Bm$	Bingham	$\frac{\tau_0 \ell}{\eta v}$	momentum
$Bi$	Biot	$\frac{h_1 \ell}{\lambda_2}$	heat
$Bi$	Biot	$\frac{k_1 \ell}{D_2}$	species
$Fo$	Fourier	$\frac{D t}{\ell^2}$	species
$Fo$	Fourier	$\frac{a t}{\ell^2}$	heat
$Gz$	Graetz	$\frac{D L}{\ell^2 v}$	species
$Gz$	Graetz	$\frac{a L}{\ell^2 v}$	heat
$Gr$	Grashof	$\frac{g \ell^3}{v^2} \beta \Delta T$	heat
$Gr$	Grashof	$\frac{g \ell^3}{v^2} \gamma \Delta c$	species
$Le$	Lewis	$\frac{a}{D}$	heat, species
$Nu$	Nusselt	$\frac{h \ell}{\lambda}$	heat
$Pe$	Peclet	$\frac{v \ell}{a}$	heat
$Pe$	Peclet	$\frac{v \ell}{D}$	species
$Po$	Power number	$\frac{P}{\rho N^3 D^5}$	Stirrers and pumps
$Pr$	Prandtl	$\frac{\nu}{a}$	heat
$Ra$	Rayleigh	$Gr \times Pr$	heat
$Ra$	Rayleigh	$Gr \times Sc$	species
$Re$	Reynolds	$\frac{\rho v \ell}{\eta}$	momentum
$Sc$	Schmidt	$\frac{\nu}{D}$	species
$Sh$	Sherwood	$\frac{k \ell}{D}$	species

# Microscopic balances

All equations are given in Cartesian coordinates  $(x_1, x_2, x_3) \equiv (x, y, z)$  where the index  $i$  indicates the direction. E.g.  $v_y$  corresponds to  $v_2$ , being the velocity component in the  $y$  direction.

## Mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_1}(\rho v_1) + \frac{\partial}{\partial x_2}(\rho v_2) + \frac{\partial}{\partial x_3}(\rho v_3) = 0$$

## Momentum

For each velocity component  $v_i$ :

### General form

$$\rho \left( \frac{\partial v_i}{\partial t} + v_1 \frac{\partial v_i}{\partial x_1} + v_2 \frac{\partial v_i}{\partial x_2} + v_3 \frac{\partial v_i}{\partial x_3} \right) = - \left( \frac{\partial}{\partial x_1} \tau_{1i} + \frac{\partial}{\partial x_2} \tau_{2i} + \frac{\partial}{\partial x_3} \tau_{3i} \right) - \frac{\partial p}{\partial x_i} + \rho g_i$$

### Newtonian fluids, constant $\eta$

$$\tau_{ji} = -\eta \left( \frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) \rightarrow \rho \left( \frac{\partial v_i}{\partial t} + v_1 \frac{\partial v_i}{\partial x_1} + v_2 \frac{\partial v_i}{\partial x_2} + v_3 \frac{\partial v_i}{\partial x_3} \right) = \eta \left( \frac{\partial^2 v_i}{\partial x_1^2} + \frac{\partial^2 v_i}{\partial x_2^2} + \frac{\partial^2 v_i}{\partial x_3^2} \right) - \frac{\partial p}{\partial x_i} + \rho g_i$$

## Internal energy (no dissipation, no shock waves)

### general form

$$\rho C_p \left( \frac{\partial T}{\partial t} + v_1 \frac{\partial T}{\partial x_1} + v_2 \frac{\partial T}{\partial x_2} + v_3 \frac{\partial T}{\partial x_3} \right) = - \left( \frac{\partial \phi''_{q,1}}{\partial x_1} + \frac{\partial \phi''_{q,2}}{\partial x_2} + \frac{\partial \phi''_{q,3}}{\partial x_3} \right) + Q'''$$

### Fourier's law, constant $\lambda$

$$\phi''_{q,i} = -\lambda \frac{\partial T}{\partial x_i} \rightarrow \rho C_p \left( \frac{\partial T}{\partial t} + v_1 \frac{\partial T}{\partial x_1} + v_2 \frac{\partial T}{\partial x_2} + v_3 \frac{\partial T}{\partial x_3} \right) = \lambda \left( \frac{\partial^2 T}{\partial x_1^2} + \frac{\partial^2 T}{\partial x_2^2} + \frac{\partial^2 T}{\partial x_3^2} \right) + Q'''$$

## Species

### general form for species A

$$\left( \frac{\partial c_A}{\partial t} + v_1 \frac{\partial c_A}{\partial x_1} + v_2 \frac{\partial c_A}{\partial x_2} + v_3 \frac{\partial c_A}{\partial x_3} \right) = - \left( \frac{\partial \phi''_{A,1}}{\partial x_1} + \frac{\partial \phi''_{A,2}}{\partial x_2} + \frac{\partial \phi''_{A,3}}{\partial x_3} \right) + R_A'''$$

### Fick's law, constant $D$

$$\phi''_{A,i} = -D_A \frac{\partial c_A}{\partial x_i} \rightarrow \left( \frac{\partial c_A}{\partial t} + v_1 \frac{\partial c_A}{\partial x_1} + v_2 \frac{\partial c_A}{\partial x_2} + v_3 \frac{\partial c_A}{\partial x_3} \right) = D_A \left( \frac{\partial^2 c_A}{\partial x_1^2} + \frac{\partial^2 c_A}{\partial x_2^2} + \frac{\partial^2 c_A}{\partial x_3^2} \right) + R_A'''$$

# Macroscopic balances

subscript '1': inlet, subscript '2': outlet,  $\phi_m$  (kg/s): mass flow rate,  $\phi_v$  (m<sup>3</sup>/s): flow rate,  $\phi_w$  (W): mechanical energy added (work, e.g. pump) in,  $\phi_q$  (W): internal energy added,  $V$  (m<sup>3</sup>): control volume,  $c_A$  (kg/m<sup>3</sup>, mol/m<sup>3</sup>): concentration of species A,  $\langle v \rangle$  (m/s): cross-sectional averaged velocity in a duct or in/upstream/downstream of a local restriction,  $e_{fr}$  (J/kg): energy dissipation, which can be calculated by

$$e_{fr} = \underbrace{\sum_i \left( 4f \frac{1}{2} \langle v \rangle^2 \frac{L}{D_h} \right)_i}_{\text{ducts}} + \underbrace{\sum_j \left( K_w \frac{1}{2} \langle v \rangle^2 \right)_j}_{\text{restrictions}}$$

with  $K_w$ : local friction loss factor,  $f$ : Fanning friction coefficient,  $D_h \equiv 4A/S$ : hydraulic diameter

## Mass

### transient

$$\frac{d}{dt} (\rho V) = \phi_{m,1} - \phi_{m,2}$$

### stationary

$$\phi_{m,1} = \phi_{m,2}$$

## Total energy

$$e \equiv u + \frac{1}{2} \langle v \rangle^2 + gz$$

### transient

$$\frac{d}{dt} (\rho e V) = \phi_{m,1} \left( e + \frac{p}{\rho} \right)_1 - \phi_{m,2} \left( e + \frac{p}{\rho} \right)_2 + \phi_q + \phi_w$$

### stationary

$$0 = \phi_m \left( e_1 - e_2 + \left( \frac{p}{\rho} \right)_1 - \left( \frac{p}{\rho} \right)_2 \right) + \phi_q + \phi_w$$

## Mechanical energy

$$e_m \equiv \frac{1}{2} \langle v \rangle^2 + gz$$

### transient

$$\frac{d}{dt} (\rho e_m V) = \phi_m \left( e_{m,1} - e_{m,2} + \left( \frac{p}{\rho} \right)_1 - \left( \frac{p}{\rho} \right)_2 \right) + \int_{V(t)} \rho \left( \frac{\partial v_i}{\partial x_i} \right) dV + \phi_w - \phi_m e_{fr} \quad \boxed{\phi_{m,1} = \phi_{m,2}}$$

$$\rho V \frac{de_m}{dt} = \phi_m \left( e_{m,1} - e_{m,2} + \frac{p_1}{\rho} - \frac{p_2}{\rho} \right) + \phi_w - \phi_m e_{fr} \quad \boxed{\phi_{m,1} = \phi_{m,2}, \rho = \text{constant}}$$

### stationary

$$0 = \phi_m \left( e_{m,1} - e_{m,2} - \int_1^2 \left( \frac{1}{\rho} \right) dp \right) + \phi_w - \phi_m e_{fr}$$

---

## Bernoulli equation

$$\frac{p}{\rho} + gz + \frac{1}{2}(v)^2 = \text{constant along a streamline.}$$

## Internal energy (heat)

### transient

$$\frac{d}{dt}(\rho u V) = \phi_m (u_1 - u_2) - \int_{V(t)} \rho \left( \frac{\partial v_i}{\partial x_i} \right) dV + \phi_q + \phi_m e_{fr} \quad \boxed{\phi_{m,1} = \phi_{m,2}}$$

$$\rho V \frac{du}{dt} = \phi_m (u_1 - u_2) + \phi_q + \phi_m e_{fr} \quad \boxed{\phi_{m,1} = \phi_{m,2}, \rho = \text{constant}}$$

### stationary

$$0 = \phi_m \left( u_1 - u_2 - \int_1^2 \rho d \left( \frac{1}{\rho} \right) \right) + \phi_q + \phi_m e_{fr}$$

## Momentum

### transient

$$\frac{d}{dt}(\rho v_i V) = \phi_{m,1} v_{i,1} - \phi_{m,2} v_{i,2} + \sum F_i$$

### stationary

$$0 = \phi_m (v_{i,1} - v_{i,2}) + \sum F_i$$

## Species

### transient

$$\frac{d}{dt}(c_A V) = \phi_{V,1} c_{A,1} - \phi_{V,2} c_{A,2} + P_A$$

### stationary

$$0 = \phi_V (c_{A,1} - c_{A,2}) + P_A$$

# Important correlations

## Heat transfer

### Conduction only

Around a sphere in an infinite medium	$Nu = 2$	stationary
Inside a large, flat plate	$Nu = 1$	stationary
Inside a long annulus between diameters $D_1$ and $D_2$	$Nu_{D_2} = \frac{2}{\ln(D_2/D_1)}$	stationary
Inside a large plate/sphere/long cylinder	$Nu = 4.93/6.6/5.8$	Long terms

### forced convection

Laminar flow in tubes: developing along $x$ developing, averaged over $0 \leq x \leq L$ developed	$Nu(x) = 1.08Gz(x)^{-1/3}$ $\langle Nu \rangle_L = 1.62Gz(L)^{-1/3}$  $Nu = \langle Nu \rangle = 3.66$	$Gz(x) < 0.05$ $Gz(L) < 0.05$
Turbulent flow in tubes	$Nu = 0.027Re^{0.8}Pr^{1/3}$	$Re > 10^4, Pr \geq 0.7$
Flat plate parallel to the flow, developing along $x$	$Nu(x) = 0.332Re(x)^{0.5}Pr^{1/3}$	$Re(x) \equiv \frac{\rho V_{x=0} x}{\eta} < 3 \times 10^5$
Long cylinders perpendicular to flow	$\langle Nu \rangle = 0.57Re^{0.5}Pr^{1/3}$	$10 < Re < 10^4, Pr > 0.7, Pe \gg 1$
Flow around spheres	$\langle Nu \rangle = 2 + 0.66Re^{0.5}Pr^{1/3}$	$10 < Re < 10^4, Pr > 0.7, Pe \gg 1$

### free convection

Single vertical plate	$\langle Nu \rangle = 0.52Ra^{1/4}$ $\langle Nu \rangle = 0.12Ra^{1/3}$	$10^4 < Ra < 10^8$ (laminar) $Ra > 10^8$ (turbulent)
Between two large horizontal plates	$\langle Nu \rangle = 1$ $\langle Nu \rangle = 0.15Ra^{1/4}$ $\langle Nu \rangle = 0.17Ra^{1/3}$	$Ra < 10^3$ $10^4 < Ra < 10^7$ (laminar) $Ra > 10^7$ (turbulent)
Above single hot plate	$\langle Nu \rangle = 0.17Ra^{1/3}$	$Ra > 10^8$

## Species transfer

### Diffusion only

Around a sphere in an infinite medium	$Sh = 2$	stationary
Inside a large, flat plate	$Sh = 1$	stationary
Inside a long annulus between diameters $D_1$ and $D_2$	$Sh_{D_2} = \frac{2}{\ln(D_2/D_1)}$	stationary
Inside a large plate/sphere/long cylinder	$Sh = 4.93/6.6/5.8$	Long terms

## forced convection

Laminar flow in tubes: developing along x	$Sh(x) = 1.08Gz(x)^{-1/3}$	$Gz(x) < 0.05$
developing, averaged over $0 \leq x \leq L$	$\langle Sh \rangle_L = 1.62Gz(L)^{-1/3}$	$Gz(L) < 0.05$
developed	$Sh = \langle Sh \rangle = 3.66$	$Gz(x) > 0.1$
Turbulent flow in tubes	$Sh = 0.027Re^{0.8}Sc^{1/3}$	$Re > 10^4, Sc \geq 0.7$
Flat plate parallel to the flow, developing along x	$Sh(x) = 0.332Re(x)^{0.5}Sc^{1/3}$	$Re(x) \equiv \frac{\rho v_{x=0} x}{\eta} < 3 \times 10^5$
Long cylinders perpendicular to flow	$\langle Sh \rangle = 0.42Sc^{1/5} + 0.57Re^{0.5}Sc^{1/3}$	$1 < Re < 10^4, Sc > 0.7, Pe \gg 1$
Flow around spheres	$\langle Sh \rangle = 2 + 0.66Re^{0.5}Sc^{1/3}$	$10 < Re < 10^4, Sc > 0.7, Pe \gg 1$

## free convection

Single vertical plate	$\langle Sh \rangle = 0.55Ra^{1/4}$ $\langle Sh \rangle = 0.13Ra^{1/3}$	$10^4 < Ra < 10^8$ (laminar) $Ra > 10^8$ (turbulent)
Between two large horizontal plates	$\langle Sh \rangle = 1$ $\langle Sh \rangle = 0.54Ra^{1/4}$ $\langle Sh \rangle = 0.17Ra^{1/3}$	$Ra < 10^3$ $10^4 < Ra < 10^7$ (laminar) $Ra > 10^7$ (turbulent)
Above single plate of high concentration	$\langle Sh \rangle = 0.54Ra^{1/4}$ $\langle Sh \rangle = 0.15Ra^{1/3}$	$10^4 < Ra < 10^7$ $10^7 < Ra < 10^{11}$

## Flow

Laminar flow in tubes	$4f = \frac{64}{Re}$	
Turbulent flow in smooth tubes (Blasius)	$4f = 0.316Re^{-0.25}$	$4 \times 10^3 < Re < 10^5$
Turbulent flow in smooth tubes (McAdams)	$4f = 0.184Re^{-0.20}$	$10^4 < Re < 10^6$

## Combined species and heat transfer

### Relation of Chilton and Colburn (for turbulent flow)

$$k = \frac{h}{\rho C_p} \left( \frac{\mathbb{D}}{a} \right)^{2/3} = \frac{h}{\rho C_p} Le^{-2/3}$$

### Analogy

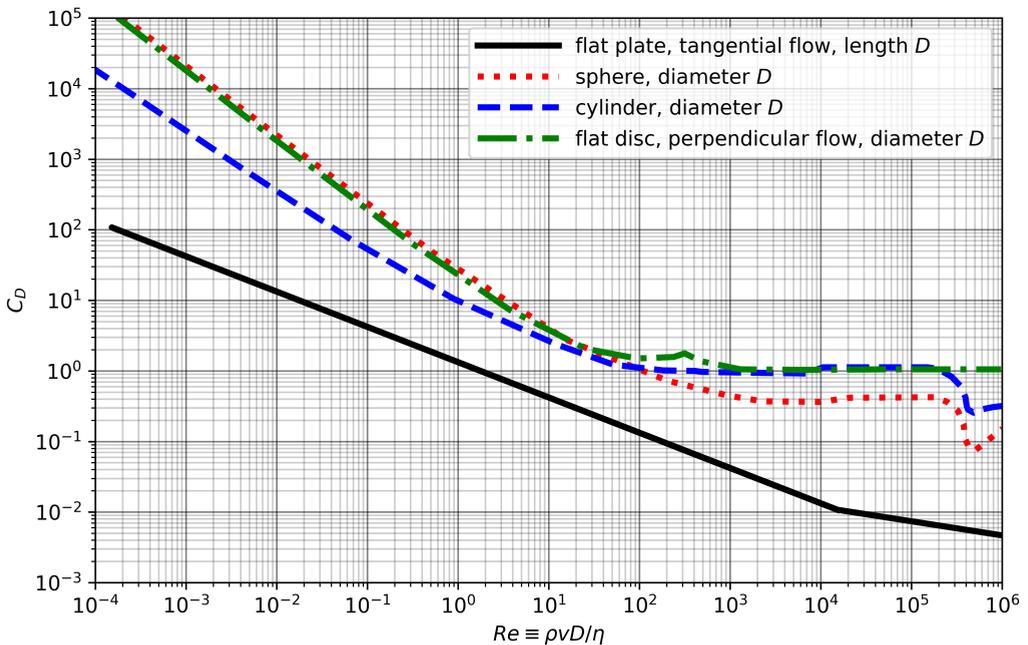
Heat		Species
$\rho C_p T$	Concentration	$c_{kg,mol}$
$\Delta T$	Driving difference	$\Delta c_{kg,mol}$
$\phi_q = \phi_V \cdot \rho \cdot C_p \cdot T$	Convection	$\phi_{kg,mol} = \phi_V \cdot c_{kg,mol}$
$\phi_q'' = -\lambda \frac{dT}{dX}$	Molecular transport	$\phi_{kg,mol}'' = -\mathbb{D} \frac{dc_{kg,mol}}{dX}$
$\phi_q = h \cdot A \cdot \Delta T$	based on transfer coefficient	$\phi_{kg,mol} = k \cdot A \cdot \Delta c_{kg,mol}$
$FO = \frac{at}{\varrho^2}$	Fourier number	$FO = \frac{\mathbb{D}t}{\varrho^2}$
$Nu$	Dimensionless transfer coefficient	$Sh$

# Drag and friction

## Drag coefficients around objects

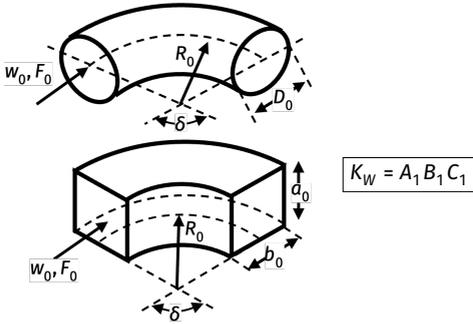
$$F_D = C_D \cdot A_{\perp} \cdot \frac{1}{2} \rho v_{\infty}^2 \quad \text{with } A_{\perp} \text{ the cross-sectional area}$$

Object	$Re$	$C_D$
Flat plate, perpendicular flow, width $W$ , height $D$	$Re > 10^3$	$W/D$
		1    1.18
		5    1.2
		10   1.2
		20   1.5
		30   1.6
$\infty$ 1.95		
Flat plate, tangential flow, length $L$	Laminar $Re < 10^7$	$1.33Re^{-0.5}$ $0.074Re^{-0.2}$
Sphere, diameter $D$	$Re < 1$	$24/Re$
Cylinder, perpendicular flow, width $W$ , diameter $D$	$10^3 < Re < 3 \times 10^5$	$W/D$
		1    0.63
		5    0.8
		10   0.83
		20   0.93
		30   1.0
$\infty$ 1.2		

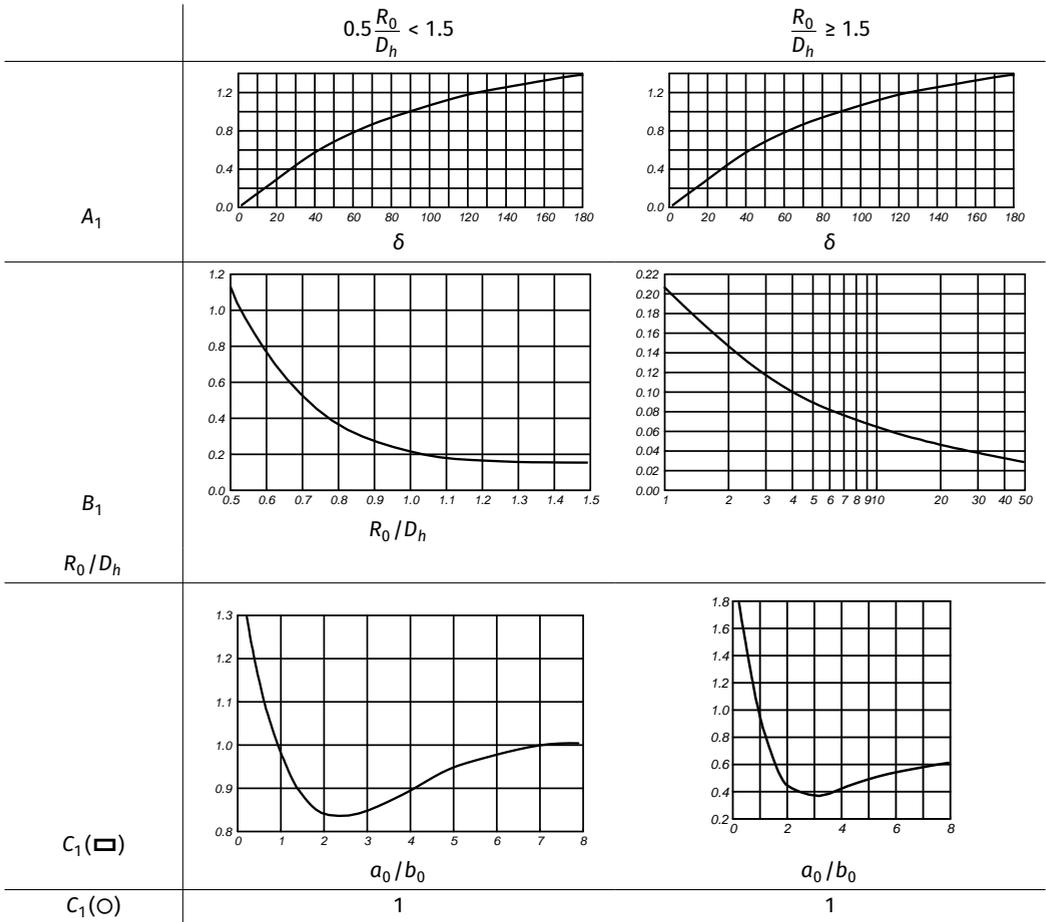


# Friction coefficients by local restrictions

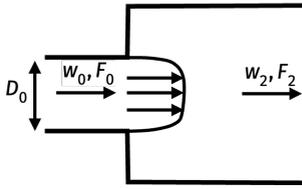
sharp and smooth bends ( $Re > 3 \times 10^5$ )



- $D_0, F_0$  = tube diameter/area
- $a_0, b_0$  = height/width rectangular duct
- $\delta$  = bend angle
- $D_h$  = hydraulic diameter
- $w_0$  = average velocity
- $R_0$  = bend radius
- $Re = w_0 D_h / \nu$



## sudden expansion and contraction



$$\Delta p = K_W \cdot \frac{1}{2} \rho w_0^2$$

$D_0, F_0, S_0$  = inlet diameter/area/perimeter

$w_0$  = inlet average velocity

$w_2$  = outlet average velocity

$F_2$  = outlet area

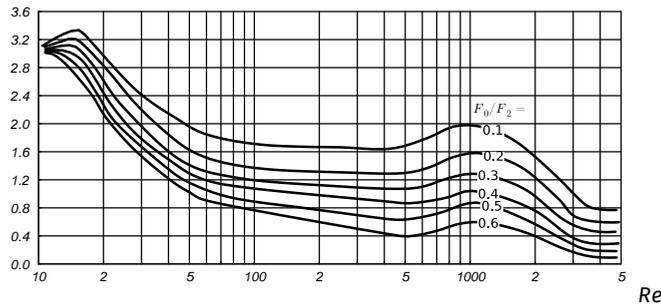
$Re = w_0 D_h / \nu$ ,  $D_h = 4F_0 / S_0$

$Re$

$K_W$

$1 < Re < 8$

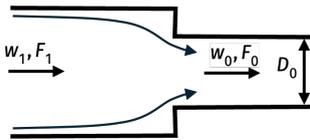
$\frac{26}{Re}$



$10 < Re < 3.5 \times 10^3$

$Re \geq 3.5 \times 10^3$

$\left(1 - \frac{F_0}{F_2}\right)^2$



$$\Delta p = K_W \cdot \frac{1}{2} \rho w_0^2$$

$D_0, F_0, S_0$  = outlet diameter/area/perimeter

$w_0$  = outlet average velocity

$w_1$  = inlet average velocity

$F_1$  = inlet area

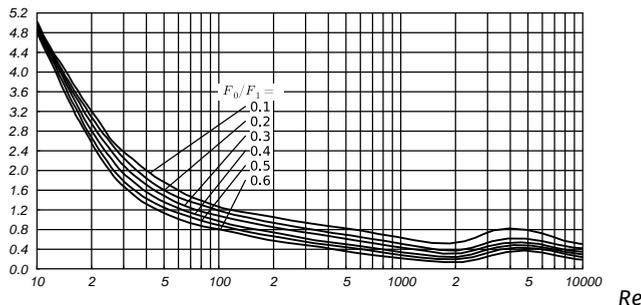
$Re = w_0 D_h / \nu$ ,  $D_h = 4F_0 / S_0$

$Re$

$K_W$

$1 < Re < 8$

$\frac{27}{Re}$

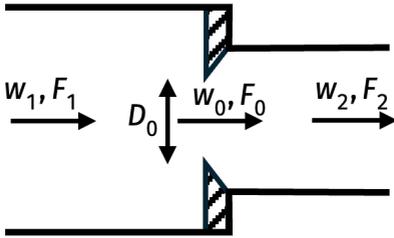


$10 < Re < 10^4$

$Re \geq 10^4$

$0.5 \left(1 - \frac{F_0}{F_1}\right)$

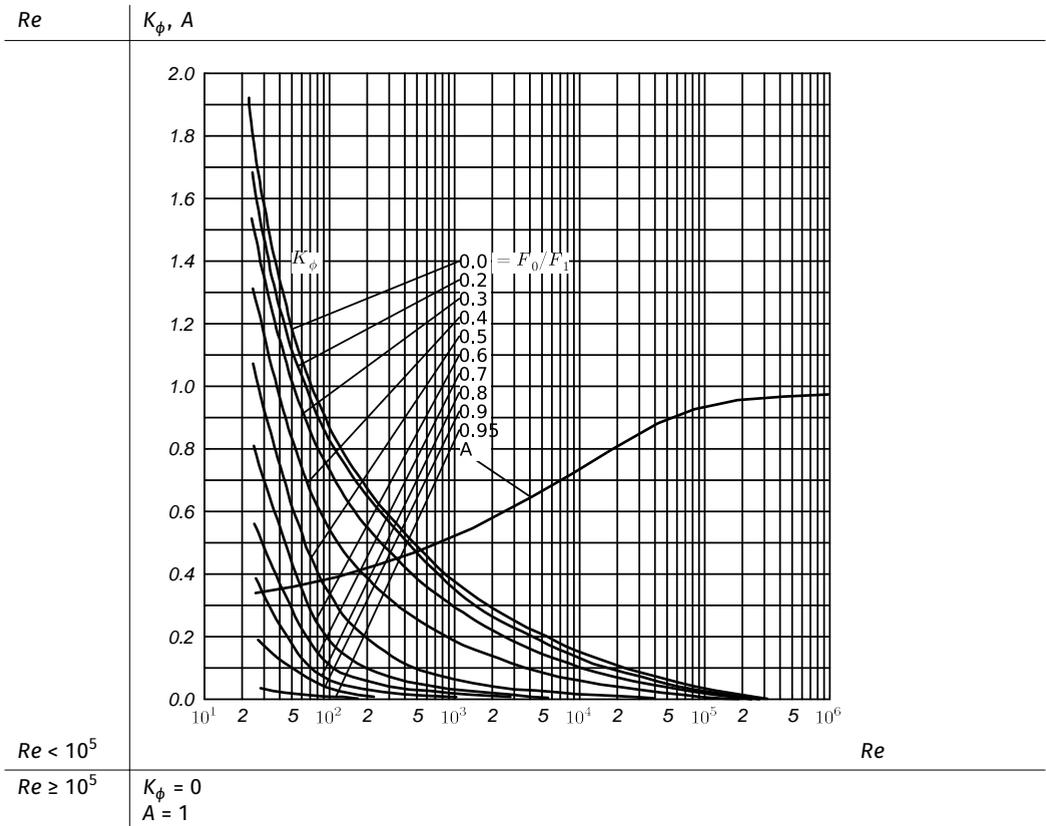
sharp-edged orifices (thickness <1.5% of  $D_h$ )



$F_0, S_0, D_0$  = orifice area/perimeter/diameter  
 $F_1$  = inlet area  
 $F_2$  = outlet area  
 $w_0, w_1, w_2$  = average velocity  
 $Re = w_0 D_h / \nu, D_h = 4F_0 / S_0$

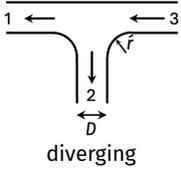
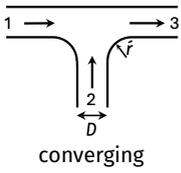
$$K_W = K_\phi + A \left( 0.707 \sqrt{1 - \frac{F_0}{F_1} + 1 - \frac{F_0}{F_2}} \right)^2$$

$$\Delta p = K_W \cdot \frac{1}{2} \rho w_0^2$$



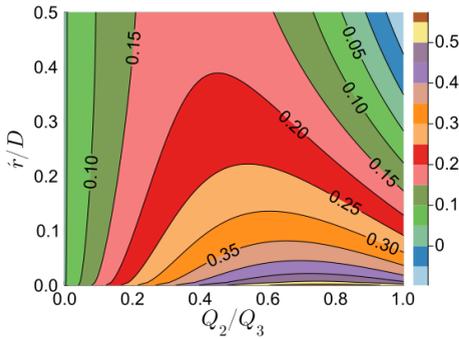
## converging and diverging T-junctions ( $Re \equiv w_3 D / \nu > 10^5$ )

$$\Delta p = K_W \cdot \frac{1}{2} \rho w_3^2$$

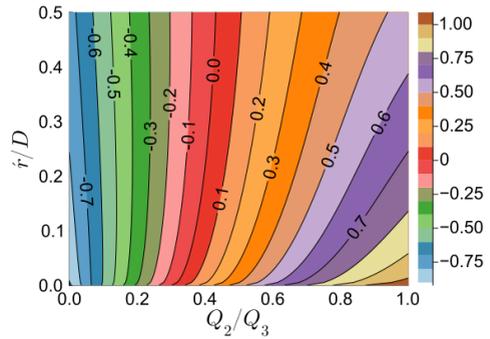


$$\begin{aligned} \textcircled{1} \quad K_{1-3} &= 0.045 + \left[ 1.38 - 1.94 \left( \frac{\dot{r}}{D} \right)^{0.5} + 1.34 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_2}{Q_3} \right) - \\ &\quad \left[ 0.90 - 0.95 \left( \frac{\dot{r}}{D} \right)^{0.5} + 1.23 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_2}{Q_3} \right)^2 \\ \textcircled{2} \quad K_{2-3} &= \left[ 1.09 - 0.80 \left( \frac{\dot{r}}{D} \right)^{0.5} \right] - \left[ 0.53 + 1.27 \left( \frac{\dot{r}}{D} \right)^{0.5} - 1.86 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_1}{Q_3} \right)^2 - \\ &\quad \left[ 1.48 - 2.28 \left( \frac{\dot{r}}{D} \right)^{0.5} + 1.80 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_1}{Q_3} \right)^2 \\ \textcircled{3} \quad K_{3-1} &= 1.55 \left[ 0.22 - \left( \frac{Q_2}{Q_3} \right) \right]^2 - 0.03 \quad 0 \leq \left( \frac{Q_2}{Q_3} \right) \leq 0.22 \\ \textcircled{4} \quad K_{3-1} &= 0.65 \left[ \left( \frac{Q_2}{Q_3} \right) - 0.22 \right]^2 - 0.03 \quad 0.22 \leq \left( \frac{Q_2}{Q_3} \right) \leq 1 \\ \textcircled{5} \quad K_{3-2} &= \left[ 0.99 - 0.23 \left( \frac{\dot{r}}{D} \right)^{0.5} \right] - \left[ 0.82 + 0.29 \left( \frac{\dot{r}}{D} \right)^{0.5} + 0.30 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_2}{Q_3} \right) + \\ &\quad \left[ 1.02 - 0.64 \left( \frac{\dot{r}}{D} \right)^{0.5} + 0.76 \left( \frac{\dot{r}}{D} \right) \right] \left( \frac{Q_2}{Q_3} \right)^2 \end{aligned}$$

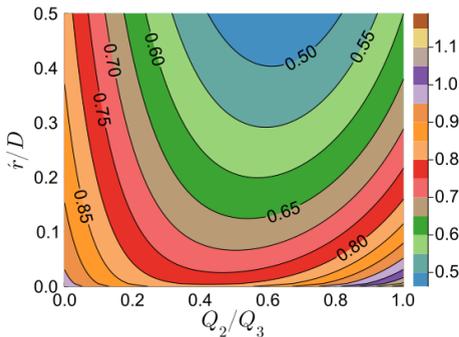
Equation ①



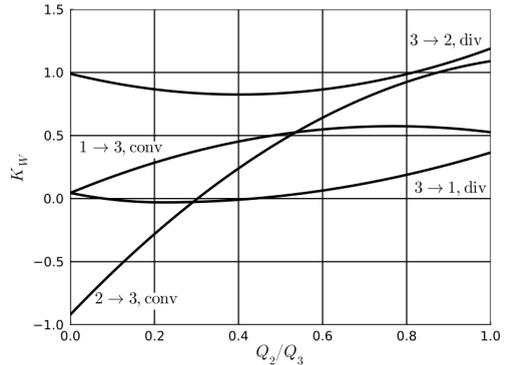
Equation ②



Equation ⑤

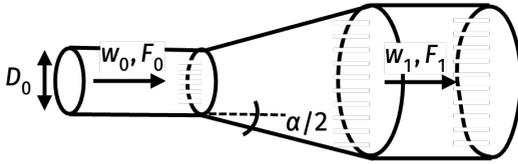


For sharp bends ( $\dot{r}/D = 0$ )



**diffusers and contractions ( $Re \equiv w_0 D_h / \nu > 10^4$ )**

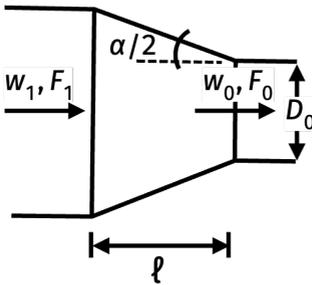
$$\Delta p = K_W \cdot \frac{1}{2} \rho w_0^2 \quad D_h = 4F_0 / S_0$$



$D_0, F_0, S_0$  = inlet diameter/area/perimeter  
 $w_0$  = inlet average velocity  
 $w_1$  = outlet average velocity  
 $F_1$  = outlet area  
 $\alpha$  = diffuser angle

$K_W$

$F_0/F_1$	$\alpha = 3^\circ$	6	8	10	12	14	10	20	24	30	40	60	90	180
0	0.03	0.08	0.11	0.15	0.19	0.23	0.27	0.36	0.47	0.65	0.92	1.15	1.1	1.02
0.05	0.03	0.07	0.10	0.14	0.16	0.20	0.24	0.32	0.42	0.58	0.83	1.04	0.99	0.92
0.075	0.03	0.07	0.09	0.13	0.16	0.19	0.23	0.30	0.4	0.55	0.79	0.99	0.95	0.88
0.1	0.03	0.07	0.09	0.12	0.15	0.18	0.22	0.29	0.38	0.52	0.75	0.93	0.89	0.83
0.15	0.02	0.06	0.08	0.11	0.14	0.17	0.20	0.26	0.34	0.46	0.67	0.84	0.79	0.74
0.2	0.02	0.05	0.07	0.10	0.12	0.15	0.17	0.23	0.3	0.41	0.59	0.74	0.7	0.65
0.25	0.02	0.05	0.06	0.08	0.10	0.13	0.15	0.20	0.26	0.35	0.47	0.65	0.62	0.58
0.3	0.02	0.04	0.05	0.07	0.09	0.11	0.13	0.18	0.23	0.31	0.4	0.57	0.54	0.5
0.4	0.01	0.03	0.04	0.06	0.07	0.08	0.10	0.13	0.17	0.23	0.33	0.41	0.39	0.37
0.5	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.09	0.12	0.16	0.23	0.29	0.28	0.26
0.6	0.01	0.01	0.02	0.03	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.18	0.17	0.16



$$K_W = K' \left( 1 - \frac{F_0}{F_1} \right)$$

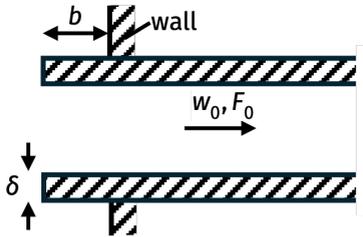
$D_0, F_0, S_0$  = outlet diameter/area/perimeter  
 $w_0$  = outlet average velocity  
 $w_1$  = inlet average velocity  
 $F_1$  = inlet area  
 $\alpha$  = contraction angle

$K'$

$l/D_h$	$\alpha = 0^\circ$	10	20	30	40	60	100	140	180
0.025	0.5	0.47	0.45	0.43	0.41	0.4	0.42	0.45	0.5
0.05	0.5	0.45	0.41	0.36	0.33	0.3	0.35	0.42	0.5
0.075	0.5	0.42	0.35	0.3	0.26	0.23	0.3	0.4	0.5
0.1	0.5	0.39	0.32	0.25	0.22	0.18	0.27	0.38	0.5
0.15	0.5	0.37	0.27	0.2	0.16	0.15	0.25	0.37	0.5
0.6	0.5	0.27	0.18	0.13	0.11	0.12	0.23	0.36	0.5

## circular or square pipe entrances and exits

$$\Delta p = K_W \frac{1}{2} \rho w_0^2$$



$D_0, F_0, S_0$  = inlet diameter/area/perimeter

$w_0$  = inlet average velocity

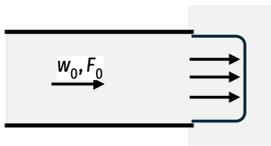
$\delta$  = pipe wall thickness

$b$  = inlet length

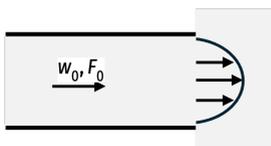
$Re = w_0 D_h / \nu$ ,  $D_h = 4F_0 / S_0$

$K_W$  for pipe entrances ( $Re \equiv w_0 D_h / \nu > 10^4$ )

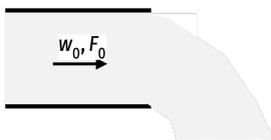
$\delta/D_h$	$b/D_h = 0$	0.002	0.005	0.01	0.02	0.05	0.1	0.2	0.3	0.5	$\infty$
0	0,50	0.57	0.63	0.68	0.73	0.8	0.86	0.92	0.97	1	1
0.004	0.5	0.54	0.58	0.63	0.67	0.74	0.8	0.86	0.9	0.94	0.94
0.008	0.5	0.53	0.55	0.58	0.62	0.68	0.74	0.81	0.85	0.88	0.88
0.012	0.5	0.52	0.53	0.55	0.58	0.63	0.68	0.75	0.79	0.83	0.83
0.016	0.5	0.51	0.51	0.53	0.55	0.58	0.64	0.7	0.74	0.77	0.77
0.02	0.5	0.51	0.51	0.52	0.53	0.55	0.6	0.66	0.69	0.72	0.72
0.024	0.5	0.5	0.5	0.51	0.52	0.53	0.58	0.62	0.65	0.68	0.68
0.03	0.5	0.5	0.5	0.51	0.52	0.52	0.54	0.57	0.59	0.61	0.61
0.04	0.5	0.5	0.5	0.51	0.51	0.51	0.51	0.52	0.52	0.54	0.54
0.05	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$\infty$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5



turbulent:  $K_W = 1$



laminar:  $K_W = 2$



All regimes:  $K_W = 0$

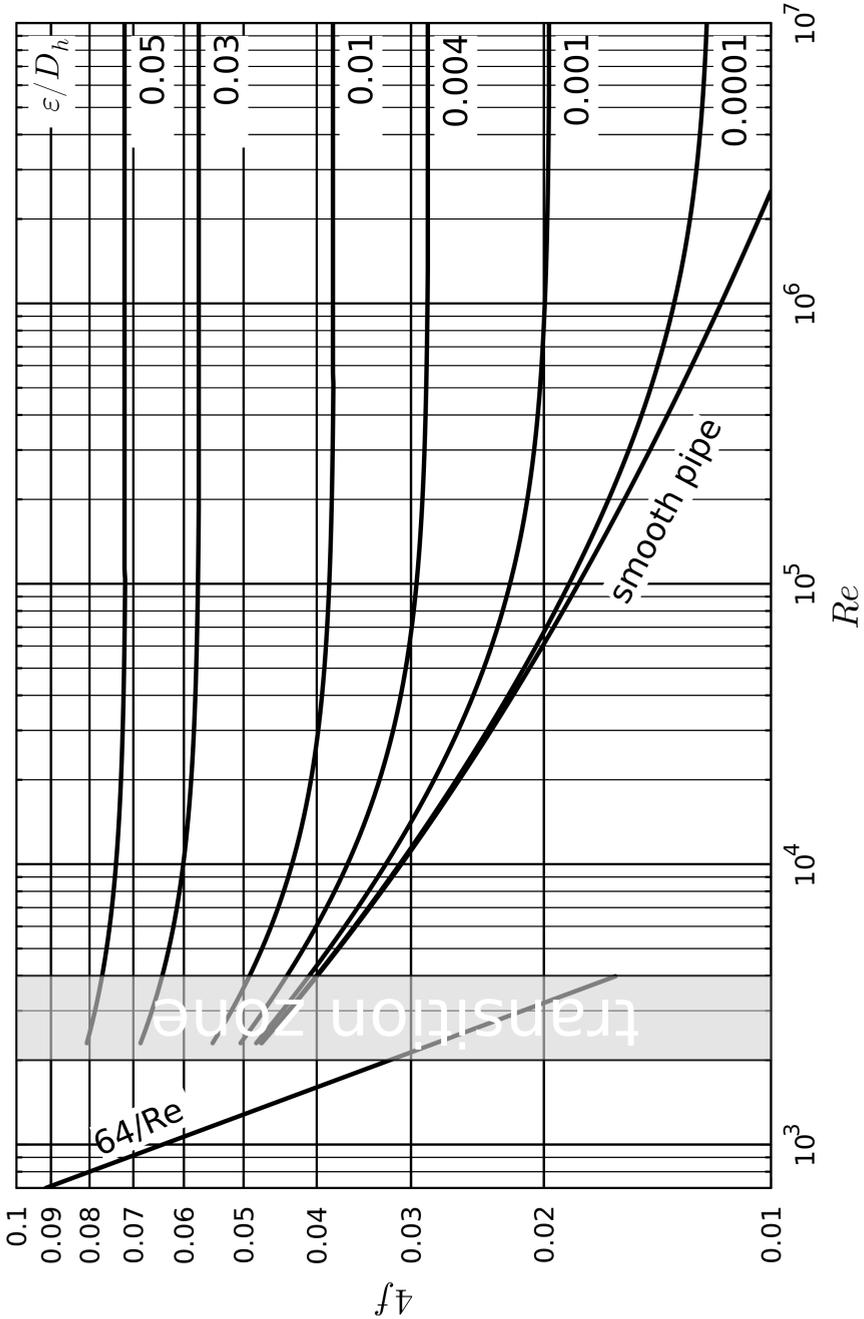
$D_0, F_0, S_0$  = outlet diameter/area/perimeter

$w_0$  = outlet average velocity

$Re = w_0 D_h / \nu$ ,  $D_h = 4F_0 / S_0$

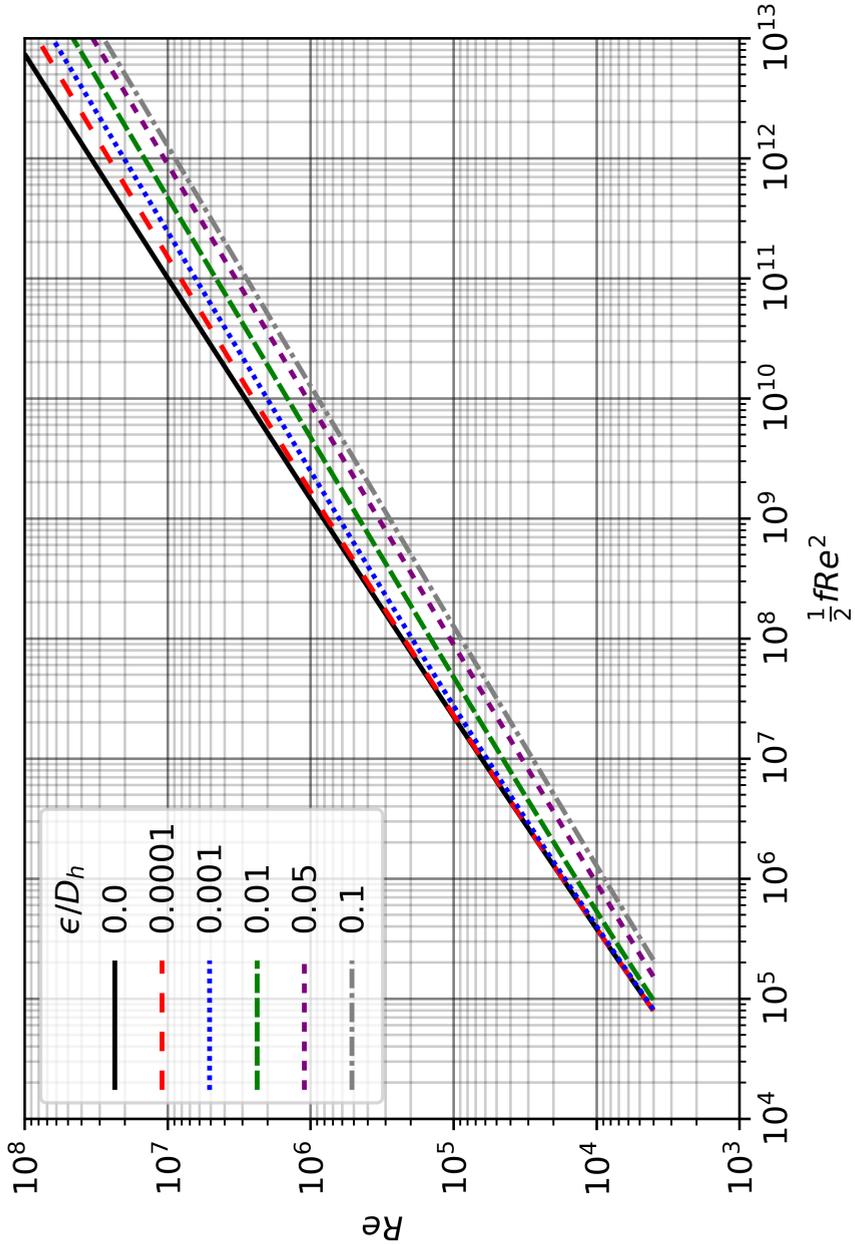
## Fanning friction factor in tubes

$$\Delta p = 4f \cdot \frac{L}{D_h} \cdot \frac{1}{2} \cdot \rho(v)^2 \quad \text{with } L \text{ the tube length}$$



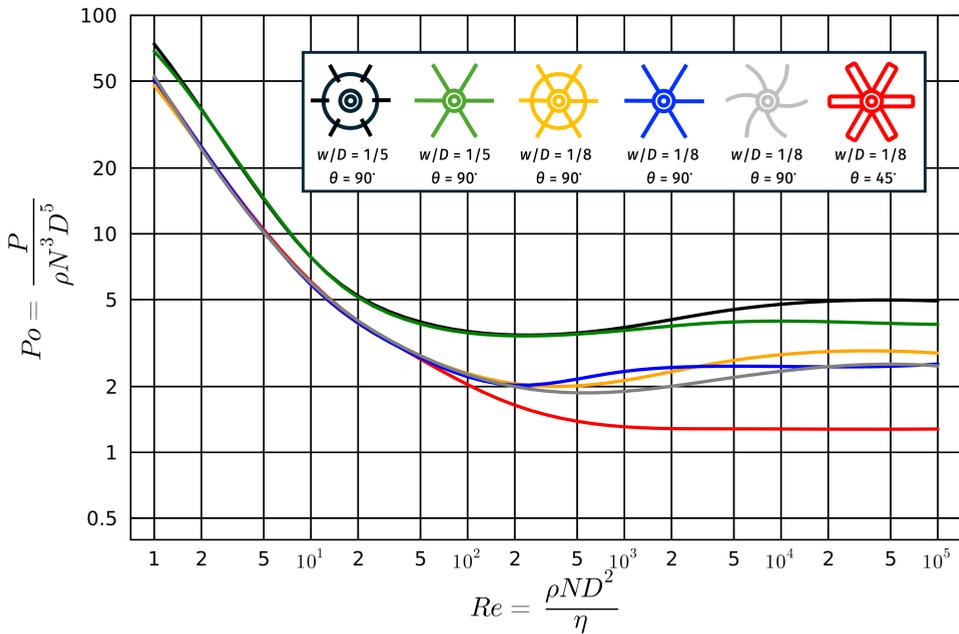
## Fanning friction factor in tubes (turbulent range)

$$\Delta p = 4f \cdot \frac{L}{D_h} \cdot \frac{1}{2} \cdot \rho(v)^2 \quad \text{with } L \text{ the tube length}$$



## Impellers: power number $Po$ vs $Re$

$P$  = power applied (W),  $N$  = impeller frequency ( $s^{-1}$ ),  $D$  = impeller diameter (m) and  $w$  = height of the impeller blade (m).



## Hydraulic diameters

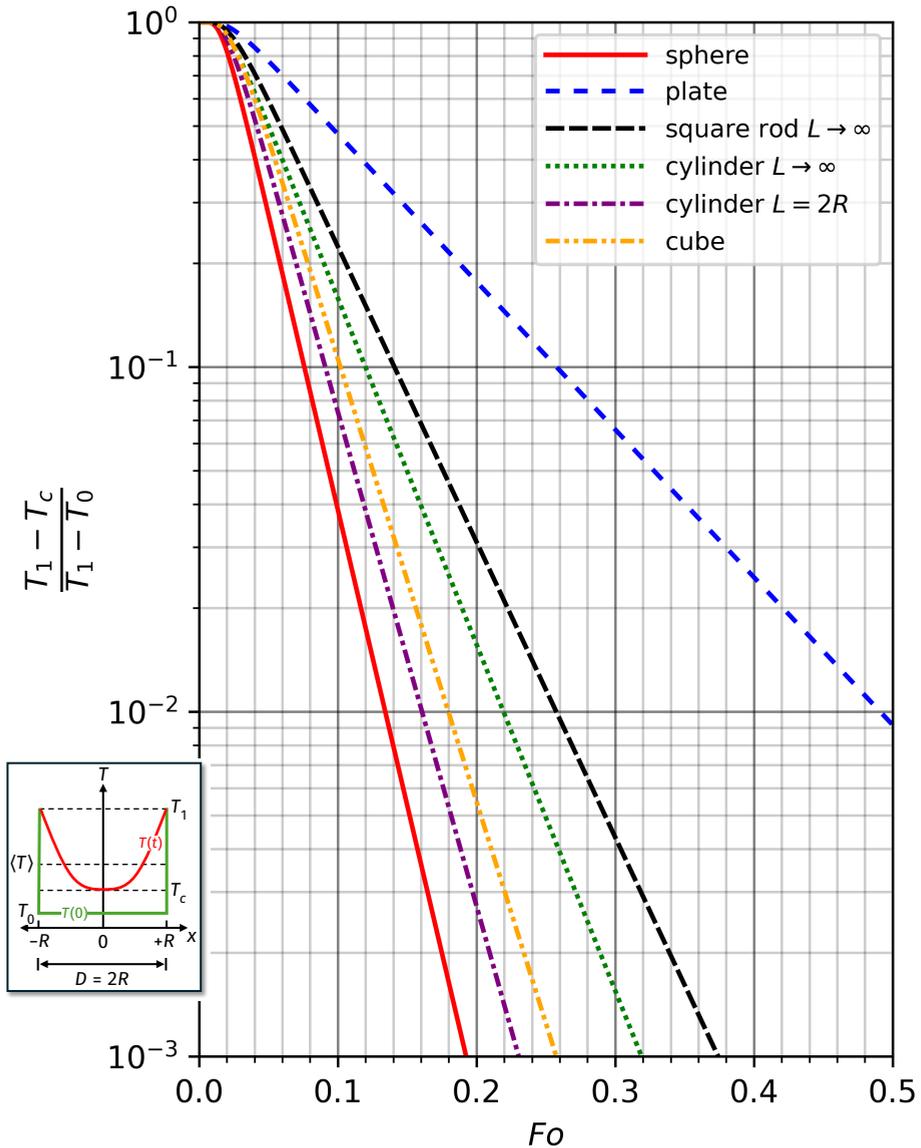
		Hydraulic diameter $D_h \equiv 4A/S$	Wetted area $A$	Wetted perimeter $S$
Fully filled, round		$D$	$\frac{\pi}{4}D^2$	$\pi D$
Partially filled, round		$\frac{D(\theta - \sin(\theta))}{\theta + 2\sin(\theta/2)}$ $\theta = 2\cos^{-1}(1 - 2H/D)$	$\frac{1}{8}D^2(\theta - \sin(\theta))$	$\frac{D}{2}\theta + D\sin(\theta/2)$
Fully filled, annulus		$D_2 - D_1$	$\frac{1}{4}\pi(D_2^2 - D_1^2)$	$\pi(D_1 + D_2)$
Fully filled, rectangular		$\frac{2WB}{W + B}$	$WB$	$2(W + B)$

# Non-stationary transport in objects

## based on the center value (large range)

Graph hereunder for temperatures, for concentrations use  $c_1$ ,  $c_c$  and  $c_0$ .

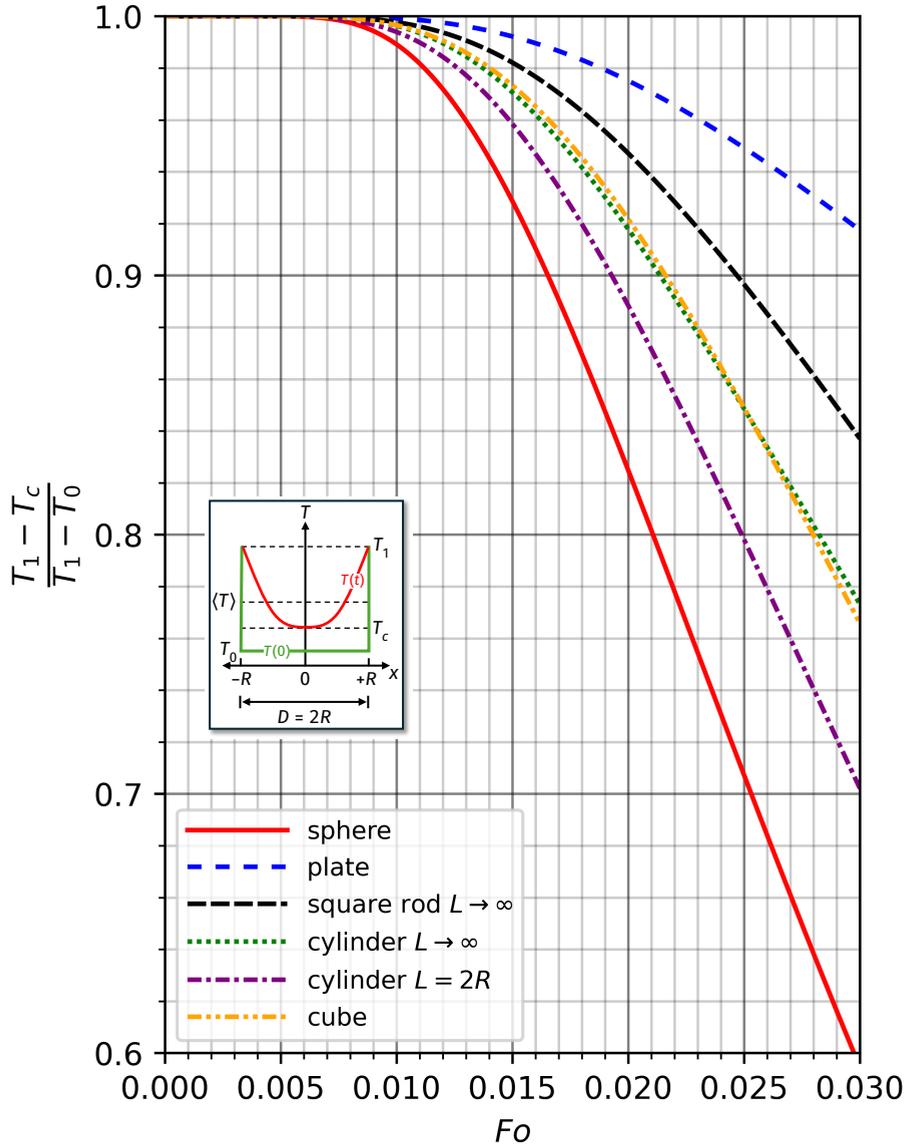
$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, Fo \equiv \frac{Dt}{D^2} \text{ (species)}$$



## based on the center value ( $Fo \leq 0.03$ )

Graph hereunder for temperatures, for concentrations use  $c_1$ ,  $c_c$  and  $c_0$ .

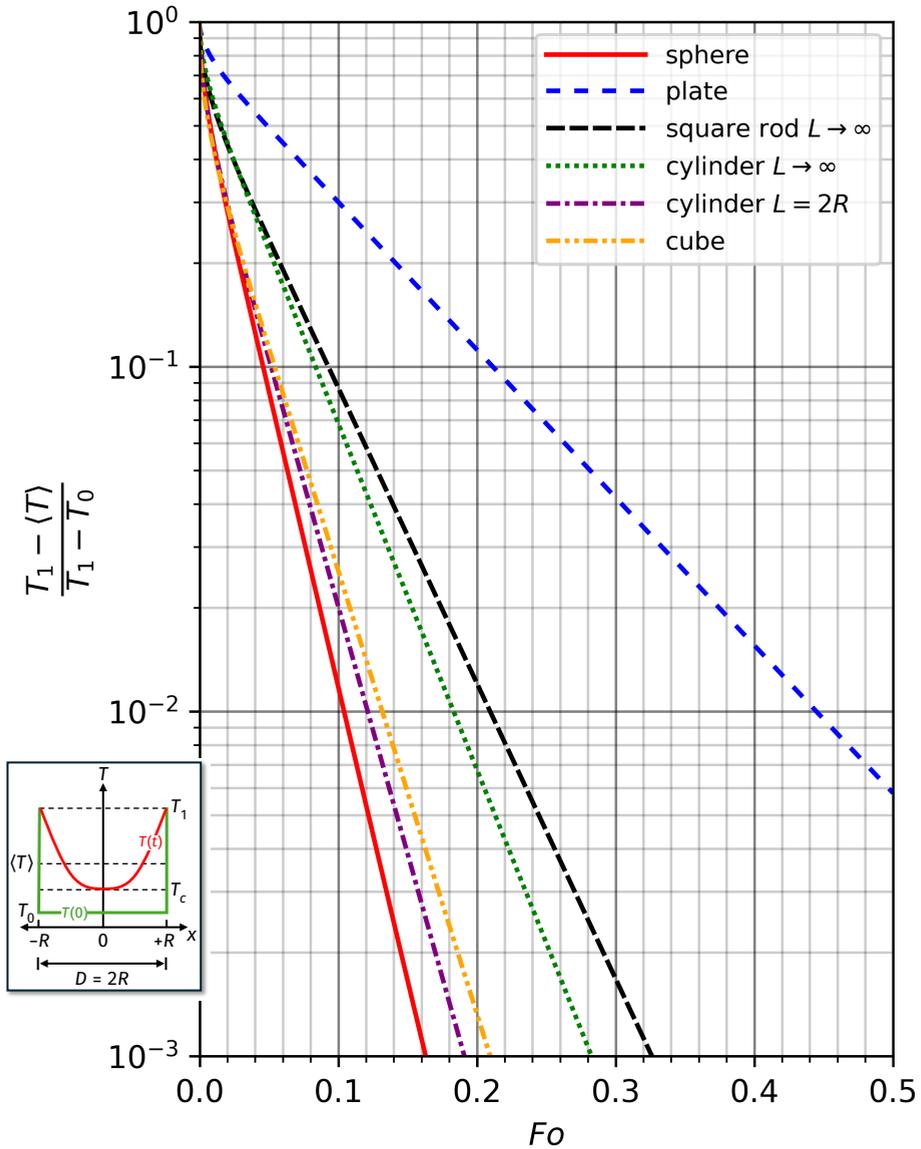
$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, \quad Fo \equiv \frac{Dt}{D^2} \text{ (species)}$$



## based on the average value (large range)

Graph hereunder for temperatures, for concentrations use  $c_1$ ,  $\langle c \rangle$  and  $c_0$ .

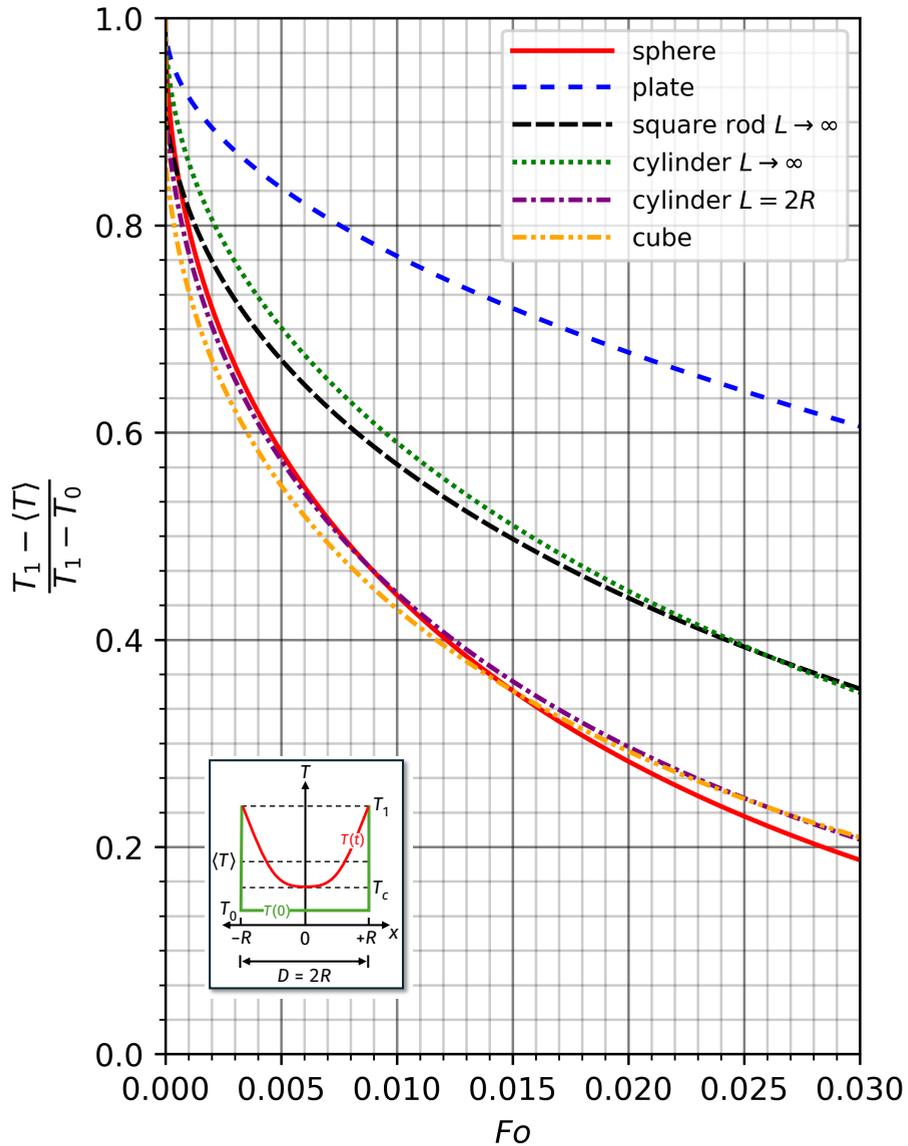
$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, Fo \equiv \frac{Dt}{D^2} \text{ (species)}$$



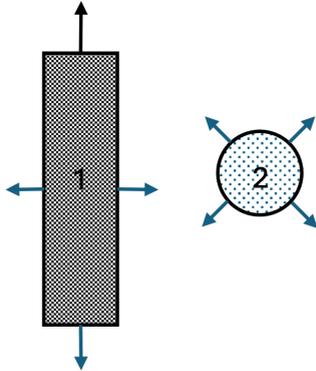
## based on the average value ( $Fo \leq 0.03$ )

Graph hereunder for temperatures, for concentrations use  $c_1$ ,  $\langle c \rangle$  and  $c_0$ .

$$Fo \equiv \frac{at}{D^2} \text{ (heat)}, \quad Fo \equiv \frac{Dt}{D^2} \text{ (species)}$$



# Radiation



$T_1, T_2 =$  surface temperature

$e_1, e_2 =$  surface emission coefficient

$A_1, A_2 =$  radiating surface area

$F_{a \rightarrow b} =$  form factor

$e_{eff} =$  effective emission coefficient

$$\phi_{net,1 \rightarrow 2} = A_1 e_{eff} \sigma (T_1^4 - T_2^4)$$

## Relevant formulas

Relation between form factors and surfaces

$$\frac{F_{1 \rightarrow 2}}{F_{2 \rightarrow 1}} = \frac{A_2}{A_1}$$

Effective emission coefficient between two bodies

$$e_{eff} = \left( \frac{1 - e_1}{e_1} + \frac{A_1}{A_2} \frac{1 - e_2}{e_2} + \frac{1}{F_{1 \rightarrow 2}} \right)^{-1}$$

## Emission coefficients of materials (T=300K)

Alloy 24ST Polished	0.09	Black Body Matt	1
Alumina, Flame sprayed	0.8	Black Enamel Paint	0.8
Aluminum Anodized	0.77	Black Epoxy Paint	0.89
Aluminum Commercial sheet	0.09	Black lacquer on iron	0.875
Aluminum Commercial Sheet	0.09	Black Parson Optical	0.95
Aluminum Foil	0.04	Black Silicone Paint	0.93
Aluminum Heavily Oxidized	0.2 - 0.31	Brass Dull Plate	0.22
Aluminum Highly Polished	0.039 - 0.057	Brass Oxidized 600° C	0.6
Aluminum paint	0.27 - 0.67	Brass Polished	0.03
Aluminum Rough	0.07	Brass Rolled Plate Natural Surface	0.06
Anodize black	0.88	Brick, fire-clay	0.75
Antimony, polished	0.28 - 0.31	Brick, red rough	0.93
Asbestos board	0.96	Cadmium	0.02
Asbestos paper	0.93 - 0.945	Carbon filament	0.77
Asphalt	0.93	Carbon pressed filled surface	0.98
Basalt	0.72	Carbon, not oxidized	0.81
Beryllium	0.18	Cast Iron, newly turned	0.44
Beryllium, Anodized	0.9	Cast Iron, turned and heated	0.60 - 0.70
Bismuth, bright	0.34	Cement	0.54

## Emission coefficients of materials (T=300K) (continued)

Clay	0.91	Paper offset	0.55
Coal	0.8	Pine	0.84
Concrete	0.85	Plaster	0.98
Concrete tiles	0.63	Plaster board	0.91
Concrete, rough	0.94	Plaster, rough	0.91
Copper electroplated	0.03	Plastics	0.90 - 0.97
Copper Nickel Alloy, polished	0.059	Platinum, polished plate	0.054 - 0.104
Copper Polished	0.023 - 0.052	Polyethylene, black plastic	0.92
Copper with thick oxide layer	0.78	Polypropylene	0.97
Cotton cloth	0.77	Polytetrafluoroethylene (PTFE)	0.92
Cromium polished	0.058	Porcelain glazed	0.93
Glass smooth	0.92 - 0.94	Porcelain, glazed	0.92
Glass, opal	0.87	PVC	0.91 - 0.93
Glass, pyrex	0.85 - 0.95	Pyrex	0.92
Gold highly polished	0.02 - 0.04	Quartz glass	0.93
Gold not polished	0.47	Rubber, foam	0.9
Granite, natural surface	0.96	Rubber, hard glossy plate	0.94
Gravel	0.28	Rubber, natural hard	0.91
Gypsum	0.85	Rubber, natural oft	0.86
Ice rough	0.985	Salt	0.34
Ice smooth	0.966	Sand	0.9
Inconel X Oxidized	0.71	Sandstone	0.59
Iron polished	0.14 - 0.38	Sapphire	0.48
Iron, dark gray surface	0.31	Sawdust	0.75
Iron, plate rusted red	0.61	Silica	0.79
Iron, rough ingot	0.87 - 0.95	Silicon Carbide	0.83 - 0.96
Lampblack paint	0.96	Silver Polished	0.02 - 0.03
Lead Oxidized	0.43	Snow	0.96 - 0.98
Lead pure unoxidized	0.057 - 0.075	Soil	0.90 - 0.95
Lime wash	0.91	Stainless Steel, polished	0.075
Limestone	0.90 - 0.93	Stainless Steel, type 301	0.54 - 0.63
Magnesia	0.72	Stainless Steel, weathered	0.85
Magnesite	0.38	Steel Galvanized New	0.23
Magnesium Oxide	0.20 - 0.55	Steel Galvanized Old	0.88
Magnesium Polished	0.07 - 0.13	Steel Oxidized	0.79
Marble White	0.95	Steel Polished	0.07
Masonry Plastered	0.93	Thoria	0.28
Mercury liquid	0.1	Tile	0.97
Mild Steel	0.20 - 0.32	Tin unoxidized	0.04
Molybdenum polished	0.05 - 0.18	Titanium polished	0.19
Mortar	0.87	Tungsten aged filament	0.032 - 0.35
Nichrome wire, bright	0.65 - 0.79	Tungsten polished	0.04
Nickel, elctroplated	0.03	Water (0 - 100°C)	0.95 - 0.963
Nickel, oxidized	0.59 - 0.86	Wood Beech, planned	0.935
Nickel, polished	0.072	Wood Oak, planned	0.885
Oak, planed	0.89	Wood, Pine	0.95
Oil paints, all colors	0.92 - 0.96	Wrought Iron	0.94
Paint	0.96	Zinc polished	0.045
Paper	0.93	Zinc Tarnished	0.25

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# Mathematics

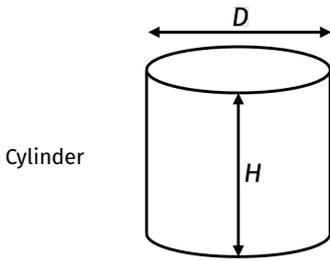
## error function

x	erf(x)	x	erf(x)	x	erf(x)
0.00	0.0000	1.00	0.8427	2.00	0.9953
0.05	0.0564	1.05	0.8624	2.05	0.9963
0.10	0.1125	1.10	0.8802	2.10	0.9970
0.15	0.1680	1.15	0.8961	2.15	0.9976
0.20	0.2227	1.20	0.9103	2.20	0.9981
0.25	0.2763	1.25	0.9229	2.25	0.9985
0.30	0.3286	1.30	0.9340	2.30	0.9989
0.35	0.3794	1.35	0.9438	2.35	0.9991
0.40	0.4284	1.40	0.9523	2.40	0.9993
0.45	0.4755	1.45	0.9597	2.45	0.9995
0.50	0.5205	1.50	0.9661	2.50	0.9996
0.55	0.5633	1.55	0.9716	2.55	0.9997
0.60	0.6039	1.60	0.9763	2.60	0.9998
0.65	0.6420	1.65	0.9804	2.65	0.9998
0.70	0.6778	1.70	0.9838	2.70	0.9999
0.75	0.7112	1.75	0.9867	2.75	0.9999
0.80	0.7421	1.80	0.9891	2.80	0.9999
0.85	0.7707	1.85	0.9911	2.85	0.9999
0.90	0.7969	1.90	0.9928	2.90	1.0000
0.95	0.8209	1.95	0.9942	2.95	1.0000

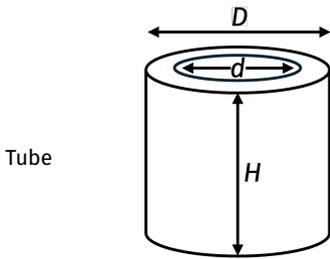
## Basic integrals

$$\begin{array}{l|l} \int x^n dx = \frac{x^{n+1}}{n+1} + C \quad (n \neq -1) & \int a dx = ax + C \\ \int \frac{1}{x} dx = \ln(x) + C & \int a^x dx = \frac{a^x}{\ln(a)} + C \\ \int e^x dx = e^x + C & \int (ax + b)^n = \frac{(ax + b)^{n+1}}{a(n+1)} + C \\ \int e^{ax} dx = \frac{1}{a} e^{ax} + C & \int \frac{c}{ax + b} dx = \frac{c}{a} \ln(ax + b) + C \end{array}$$

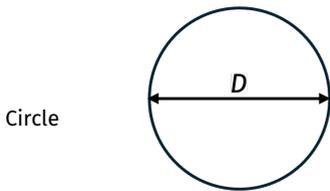
## Geometrical Measures



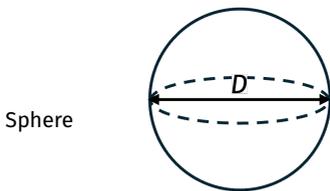
$$\begin{aligned}\text{Outer surface} &= \pi D \left( \frac{1}{2}D + H \right) \\ \text{Curved surface} &= \pi HD \\ \text{Volume} &= \frac{1}{4} \pi HD^2\end{aligned}$$



$$\text{Volume} = \frac{1}{4} \pi H (D^2 - d^2)$$



$$\begin{aligned}\text{Surface} &= \frac{1}{4} \pi D^2 \\ \text{Circumference} &= \pi D\end{aligned}$$



$$\begin{aligned}\text{Surface} &= \pi D^2 \\ \text{Volume} &= \frac{1}{6} \pi D^3\end{aligned}$$

# Properties of materials

water at  $p = 10^5 \text{ Pa}$

$T$ (°C)	$\rho$ ( $\text{kg/m}^3$ )	$\eta$ (Pa.s)	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ (W/mK)	$C_p$ J/(kgK)	$a$ ( $\text{m}^2/\text{s}$ )	Pr	$\beta$ (1/K)	$\sigma^{(*)}$ (N/m)
0.0	999.8	1.792e-03	1.792e-06	5.557e-01	4219.4	1.317e-07	13.6	-6.771e-05	7.571e-02
5.0	1000.0	1.518e-03	1.518e-06	5.678e-01	4205.0	1.350e-07	11.2	1.608e-05	7.501e-02
10.0	999.7	1.306e-03	1.306e-06	5.788e-01	4195.2	1.380e-07	9.5	8.797e-05	7.429e-02
15.0	999.1	1.137e-03	1.139e-06	5.888e-01	4188.5	1.407e-07	8.1	1.509e-04	7.356e-02
20.0	998.2	1.002e-03	1.003e-06	5.980e-01	4184.1	1.432e-07	7.0	2.068e-04	7.282e-02
25.0	997.0	8.900e-04	8.926e-07	6.065e-01	4181.3	1.455e-07	6.1	2.573e-04	7.205e-02
30.0	995.6	7.972e-04	8.007e-07	6.144e-01	4179.8	1.476e-07	5.4	3.034e-04	7.128e-02
35.0	994.0	7.191e-04	7.234e-07	6.217e-01	4179.3	1.497e-07	4.8	3.459e-04	7.049e-02
40.0	992.2	6.527e-04	6.578e-07	6.285e-01	4179.4	1.516e-07	4.3	3.855e-04	6.968e-02
45.0	990.2	5.957e-04	6.016e-07	6.348e-01	4180.1	1.534e-07	3.9	4.227e-04	6.886e-02
50.0	988.0	5.465e-04	5.531e-07	6.406e-01	4181.3	1.551e-07	3.6	4.578e-04	6.802e-02
55.0	985.7	5.036e-04	5.109e-07	6.460e-01	4183.0	1.567e-07	3.3	4.912e-04	6.717e-02
60.0	983.2	4.660e-04	4.740e-07	6.510e-01	4185.0	1.582e-07	3.0	5.233e-04	6.631e-02
65.0	980.5	4.329e-04	4.415e-07	6.556e-01	4187.3	1.597e-07	2.8	5.541e-04	6.543e-02
70.0	977.8	4.035e-04	4.127e-07	6.598e-01	4190.1	1.610e-07	2.6	5.840e-04	6.454e-02
75.0	974.8	3.774e-04	3.871e-07	6.636e-01	4193.2	1.623e-07	2.4	6.130e-04	6.363e-02
80.0	971.8	3.540e-04	3.643e-07	6.670e-01	4196.8	1.635e-07	2.2	6.414e-04	6.272e-02
85.0	968.6	3.331e-04	3.439e-07	6.701e-01	4200.7	1.647e-07	2.1	6.692e-04	6.179e-02
90.0	965.3	3.142e-04	3.255e-07	6.728e-01	4205.2	1.657e-07	2.0	6.966e-04	6.084e-02
95.0	961.9	2.971e-04	3.088e-07	6.752e-01	4210.2	1.667e-07	1.9	7.237e-04	5.989e-02

(\*) at saturation pressure

## air at $p = 10^5 \text{ Pa}$

$T$ (°C)	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ ( $\text{J}/(\text{kgK})$ )	$C_v$ ( $\text{J}/(\text{kgK})$ )	$a$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
0.0	1.276	1.722e-05	1.349e-05	2.436e-02	1005.7	716.9	1.898e-05	3.674e-03
10.0	1.231	1.772e-05	1.439e-05	2.512e-02	1005.9	717.3	2.029e-05	3.543e-03
20.0	1.189	1.821e-05	1.531e-05	2.587e-02	1006.1	717.7	2.163e-05	3.421e-03
30.0	1.149	1.869e-05	1.626e-05	2.662e-02	1006.5	718.1	2.301e-05	3.307e-03
40.0	1.113	1.917e-05	1.722e-05	2.735e-02	1006.9	718.6	2.442e-05	3.201e-03
50.0	1.078	1.964e-05	1.821e-05	2.808e-02	1007.4	719.2	2.585e-05	3.101e-03
60.0	1.046	2.010e-05	1.922e-05	2.880e-02	1008.0	719.9	2.732e-05	3.007e-03
70.0	1.015	2.056e-05	2.025e-05	2.952e-02	1008.7	720.7	2.882e-05	2.919e-03
80.0	0.986	2.101e-05	2.130e-05	3.023e-02	1009.4	721.5	3.035e-05	2.836e-03
90.0	0.959	2.146e-05	2.237e-05	3.093e-02	1010.3	722.4	3.191e-05	2.758e-03
100.0	0.933	2.190e-05	2.346e-05	3.162e-02	1011.2	723.4	3.350e-05	2.683e-03
110.0	0.909	2.233e-05	2.457e-05	3.231e-02	1012.2	724.4	3.511e-05	2.613e-03
120.0	0.886	2.276e-05	2.569e-05	3.299e-02	1013.3	725.6	3.675e-05	2.546e-03
130.0	0.864	2.319e-05	2.684e-05	3.367e-02	1014.5	726.8	3.841e-05	2.483e-03
140.0	0.843	2.361e-05	2.801e-05	3.434e-02	1015.8	728.1	4.010e-05	2.423e-03
150.0	0.823	2.403e-05	2.919e-05	3.500e-02	1017.1	729.5	4.181e-05	2.365e-03
160.0	0.804	2.444e-05	3.039e-05	3.566e-02	1018.5	730.9	4.354e-05	2.310e-03
170.0	0.786	2.485e-05	3.162e-05	3.631e-02	1020.0	732.5	4.530e-05	2.258e-03
180.0	0.769	2.525e-05	3.285e-05	3.696e-02	1021.6	734.1	4.708e-05	2.208e-03
190.0	0.752	2.565e-05	3.411e-05	3.761e-02	1023.2	735.7	4.888e-05	2.160e-03
200.0	0.736	2.605e-05	3.539e-05	3.825e-02	1025.0	737.5	5.070e-05	2.115e-03

## other fluids and gases at $p = 10^5 \text{ Pa}$ , $T = 20 \text{ }^\circ\text{C}$

Fluid	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ $\text{J}/(\text{kgK})$	$a$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
1-Butene	2.371				1544.6		3.785e-03
Acetone	790.265				2131.0		1.404e-03
Air	1.189	1.821e-05	1.531e-05	2.587e-02	1006.1	2.163e-05	3.421e-03
Ammonia	0.707	9.911e-06	1.403e-05	2.449e-02	2162.2	1.603e-05	3.569e-03
Argon	1.640	2.231e-05	1.360e-05	1.750e-02	521.6	2.045e-05	3.422e-03
Benzene	878.832	6.468e-04	7.360e-07	1.429e-01	1722.2	9.440e-08	1.209e-03
CarbonDioxide	1.815	1.467e-05	8.085e-06	1.625e-02	846.0	1.058e-05	3.471e-03
CarbonMonoxide	1.150				1042.0		3.422e-03
CarbonylSulfide	2.494				697.3		3.536e-03
CycloHexane	778.673	9.724e-04	1.249e-06		1835.6		1.207e-03
CycloPropane	1.756				1334.2		3.616e-03
Cyclopentane	745.388	3.240e-04	4.347e-07	1.285e-01	1786.6	9.651e-08	1.316e-03
Deuterium	0.165				7247.3		3.410e-03
Dichloroethane	1252.628				1298.9		1.144e-03
DiethylEther	713.587				2317.1		1.601e-03
DimethylCarbonate	1069.892				1826.1		1.233e-03
DimethylEther	1.927	9.065e-06	4.704e-06		1455.1		3.657e-03
Ethane	1.243	9.207e-06	7.404e-06	2.036e-02	1737.7	9.421e-06	3.495e-03
Ethanol	789.418	1.194e-03	1.512e-06	1.645e-01	2396.0	8.697e-08	1.084e-03
EthylBenzene	866.895	6.476e-04	7.471e-07	1.290e-01	1730.1	8.603e-08	1.005e-03
Ethylene	1.158				1520.9		3.475e-03
EthyleneOxide	1.859				1138.8		3.808e-03
Fluorine	1.560				822.4		3.420e-03
HFE143m	4.214				928.5		3.756e-03
HeavyWater	1105.334	1.246e-03	1.127e-06	5.887e-01	4199.6	1.268e-07	1.247e-04

## other fluids and gases at $p = 10^5 \text{ Pa}$ , $T = 20 \text{ }^\circ\text{C}$ (cont'd)

Fluid	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ $\text{J}/(\text{kgK})$	$a$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
Helium	0.164	1.962e-05	1.195e-04	1.535e-01	5193.2	1.801e-04	3.409e-03
Hydrogen	0.083	8.797e-06	1.064e-04	1.834e-01	14287.8	1.553e-04	3.410e-03
HydrogenChloride	1.505				810.3		3.480e-03
HydrogenSulfide	1.409	1.186e-05	8.418e-06		1013.1		3.498e-03
IsoButane	2.452	7.375e-06	3.007e-06	1.637e-02	1670.7	3.995e-06	3.735e-03
IsoButene	2.371				1612.5		3.789e-03
Isohexane	653.174				2211.6		1.395e-03
Isopentane	620.059	2.025e-04	3.266e-07	1.032e-01	2248.0	7.407e-08	1.628e-03
Krypton	3.445				249.2		3.435e-03
Methane	0.659	1.104e-05	1.674e-05	3.345e-02	2220.5	2.284e-05	3.434e-03
Methanol	791.311	5.864e-04	7.410e-07	2.013e-01	2501.4	1.017e-07	1.189e-03
MethylLinoleate	885.430				2306.0		8.399e-04
MethylLinolenate	899.230				2115.8		8.304e-04
MethylOleate	873.817				2239.4		8.390e-04
Neon	0.827				1030.4		3.410e-03
Neopentane	3.079				1691.4		3.891e-03
Nitrogen	1.150	1.757e-05	1.529e-05	2.547e-02	1041.3	2.128e-05	3.420e-03
NitrousOxide	1.816				878.2		3.473e-03
Novect649	1617.509				1099.2		1.840e-03
OrthoDeuterium	0.165				7250.4		3.410e-03
OrthoHydrogen	0.083				14086.2		3.410e-03
Oxygen	1.314	2.027e-05	1.543e-05	2.595e-02	918.9	2.149e-05	3.423e-03
ParaDeuterium	0.165				7247.5		3.410e-03
ParaHydrogen	0.083			1.906e-01	14892.2	1.548e-04	3.410e-03
Propylene	1.753	8.410e-06	4.799e-06	1.663e-02	1533.8	6.185e-06	3.577e-03

## other fluids and gases at $p = 10^5 \text{ Pa}$ , $T = 20 \text{ }^\circ\text{C}$ (cont'd)

Fluid	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ $\text{J}/(\text{kgK})$	$a$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
Propyne	1.673				1538.6		3.630e-03
R11	1488.101	4.556e-04	3.061e-07	8.824e-02	876.0	6.769e-08	1.584e-03
R113	1575.097				913.1		1.505e-03
R114	7.243				694.5		3.767e-03
R115	6.462				713.8		3.632e-03
R116	5.725	1.388e-05	2.425e-06	1.441e-02	768.0	3.277e-06	3.541e-03
R12	5.061	1.160e-05	2.292e-06	9.701e-03	607.7	3.154e-06	3.636e-03
R123	1476.668	4.427e-04	2.998e-07	7.783e-02	1013.5	5.201e-08	1.718e-03
R1233zd(E)	5.588	1.090e-05	1.951e-06		812.7		3.960e-03
R1234yf	4.790	1.216e-05	2.538e-06	1.342e-02	896.3	3.126e-06	3.699e-03
R1234ze(E)	4.798	1.214e-05	2.530e-06	1.336e-02	881.9	3.159e-06	3.717e-03
R1234ze(Z)	4.887				852.8		4.023e-03
R124	5.757	1.267e-05	2.201e-06	1.276e-02	735.7	3.013e-06	3.761e-03
R1243zf	4.036				939.2		3.705e-03
R125	5.004	1.275e-05	2.548e-06	1.364e-02	789.1	3.455e-06	3.609e-03
R13	4.327	1.413e-05	3.265e-06	1.201e-02	639.8	4.339e-06	3.522e-03
R134a	4.278	1.162e-05	2.717e-06	1.299e-02	843.5	3.600e-06	3.694e-03
R1311	8.231				349.0		3.698e-03
R14	3.625	1.699e-05	4.688e-06	1.561e-02	689.2	6.251e-06	3.460e-03
R141b	1243.487	4.318e-04	3.472e-07	9.230e-02	1147.3	6.470e-08	1.546e-03
R142b	4.238				845.4		3.762e-03
R143a	3.511	1.094e-05	3.115e-06	1.443e-02	937.4	4.386e-06	3.635e-03
R152A	2.772	1.094e-05	3.946e-06	1.367e-02	1041.1	4.737e-06	3.706e-03
R161	2.004				1244.2		3.602e-03
R21	4.357				615.7		3.820e-03

## other fluids and gases at $p = 10^5 \text{ Pa}$ , $T = 20 \text{ }^\circ\text{C}$ (cont'd)

Fluid	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ $\text{J}/(\text{kgK})$	$a$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
R218	7.891	1.214e-05	1.539e-06	1.209e-02	789.6	1.941e-06	3.698e-03
R22	3.603	1.355e-05	3.761e-06	1.118e-02	656.8	4.724e-06	3.596e-03
R227EA	7.183	1.137e-05	1.583e-06	1.295e-02	806.1	2.237e-06	3.794e-03
R23	2.896	1.467e-05	5.066e-06	1.335e-02	729.9	6.316e-06	3.508e-03
R236EA	6.471	1.070e-05	1.654e-06	1.408e-02	860.6	2.528e-06	3.900e-03
R236FA	6.459	1.075e-05	1.665e-06	1.225e-02	831.1	2.282e-06	3.871e-03
R245ca	1399.792				1371.7		1.777e-03
R245fa	5.722	1.161e-05	2.030e-06	1.529e-02	880.7	3.035e-06	3.972e-03
R32	2.163	1.314e-05	6.076e-06	1.325e-02	842.0	7.277e-06	3.580e-03
R365MFC	1267.722				1367.0		1.668e-03
R40	2.110				833.5		3.646e-03
R404A	4.076	1.202e-05	2.948e-06	1.308e-02	869.2	3.693e-06	3.634e-03
R407C	3.598	1.203e-05	3.345e-06	1.286e-02	830.3	4.306e-06	3.633e-03
R41	1.409				1111.3		3.512e-03
R410A	3.020	1.265e-05	4.190e-06	1.296e-02	816.4	5.257e-06	3.590e-03
R507A	4.128	1.197e-05	2.900e-06	1.310e-02	864.1	3.674e-06	3.630e-03
RC318	8.472				783.7		3.789e-03
SES36	1384.757				1068.0		1.791e-03
SulfurDioxide	2.676				648.3		3.652e-03
SulfurHexafluoride	6.064	1.499e-05	2.472e-06	1.262e-02	661.0	3.147e-06	3.545e-03
Toluene	866.888	5.871e-04	6.773e-07	1.317e-01	1685.4	9.016e-08	1.072e-03
Water	998.206	1.002e-03	1.003e-06	5.980e-01	4184.1	1.432e-07	2.068e-04
Xenon	5.416				160.2		3.467e-03
cis-2-Butene	2.379				1477.3		3.840e-03

## other fluids and gases at $p = 10^5 \text{ Pa}$ , $T = 20 \text{ }^\circ\text{C}$ (cont'd)

Fluid	$\rho$ ( $\text{kg}/\text{m}^3$ )	$\eta$ ( $\text{Pa}\cdot\text{s}$ )	$\nu$ ( $\text{m}^2/\text{s}$ )	$\lambda$ ( $\text{W}/\text{mK}$ )	$C_p$ $\text{J}/(\text{kgK})$	$\alpha$ ( $\text{m}^2/\text{s}$ )	$\beta$ ( $1/\text{K}$ )
m-Xylene	864.208	6.176e-04	7.146e-07	1.311e-01	1695.6	8.948e-08	9.903e-04
n-Butane	2.462	7.279e-06	2.957e-06	1.607e-02	1712.3	3.813e-06	3.797e-03
n-Decane	730.407	9.134e-04	1.251e-06	1.308e-01	2174.2	8.236e-08	1.064e-03
n-Dodecane	749.433	1.488e-03	1.986e-06	1.365e-01	2196.4	8.293e-08	9.897e-04
n-Heptane	683.812	4.121e-04	6.026e-07	1.237e-01	2221.9	8.140e-08	1.231e-03
n-Hexane	659.380	3.132e-04	4.749e-07	1.215e-01	2252.0	8.185e-08	1.369e-03
n-Nonane	718.027	6.983e-04	9.725e-07	1.281e-01	2189.6	8.149e-08	1.097e-03
n-Octane	702.609	5.441e-04	7.744e-07	1.262e-01	2209.8	8.126e-08	1.146e-03
n-Pentane	626.189	1.891e-04	3.020e-07	1.138e-01	2293.7	7.925e-08	1.583e-03
n-Propane	1.840	8.012e-06	4.354e-06	1.776e-02	1663.7	5.802e-06	3.599e-03
n-Undecane	740.298				2198.6		1.032e-03
o-Xylene	880.230	8.112e-04	9.216e-07	1.319e-01	1750.0	8.563e-08	9.551e-04
p-Xylene	861.068	6.447e-04	7.487e-07	1.279e-01	1700.5	8.735e-08	1.005e-03
trans-2-Butene	2.379				1596.3		3.838e-03

## Composition of air

Component	Volume %	Weight %
Nitrogen	78.09	75.53
Oxygen	20.95	23.14
Argon	0.93	1.28
CO2	3.00E-02	5.00E-02
Neon	1.80E-03	1.30E-03
Helium	5.00E-04	7.00E-05
Krypton	1.00E-04	3.00E-04
Xenon	8.00E-06	4.00E-05
Hydrogen	5.00E-05	3.00E-06
Ozon	1.00E-06	2.00E-06

## Henry's law constant for solubility of gases in water, $H_s = \frac{p_i}{x_i}$

T °C	Nitrogen	Oxygen	Air	Hydrogen	CO <sub>2</sub>
	10 <sup>9</sup> Pa	10 <sup>9</sup> Pa	10 <sup>9</sup> Pa	10 <sup>9</sup> Pa	10 <sup>7</sup> Pa
0	5.36	2.58	4.38	5.87	7.62
5	6.05	2.95	4.95	6.16	9.61
10	6.77	3.31	5.59	6.44	10.9
15	7.48	3.69	6.15	6.7	12.8
20	8.15	4.06	6.73	6.92	14.8
25	8.77	4.44	7.3	7.16	17.1
30	9.36	4.81	7.81	7.38	19.5
35	9.98	5.14	8.34	7.52	
40	10.5	5.42	8.82	7.61	24.5
45	11	5.71	9.23	7.7	
50	11.5	5.96	9.59	7.75	29.8
60	12.2	6.37	10.2	7.75	35.7
80	12.8	6.96	10.8	7.65	
90	12.8	7.08	10.9	7.61	
100	12.8	7.1	10.8	7.55	

## Diffusion coefficients of gases in water

Gas	Temperature (°C)	Diffusion coefficient (10 <sup>-9</sup> m <sup>2</sup> /s)
Ammonia	20	1.46
CO <sub>2</sub>	21.7	1.60
Nitrogen	25	2.34
Oxygen	21	2.33

## Diffusion coefficients of gases and vapors in air

Gas	Diffusion coefficient (10 <sup>-9</sup> m <sup>2</sup> /s)
Ammonia	28
CO <sub>2</sub>	16.4
Ethanol	11.9
Oxygen	20.6
Water	25.6

## metals

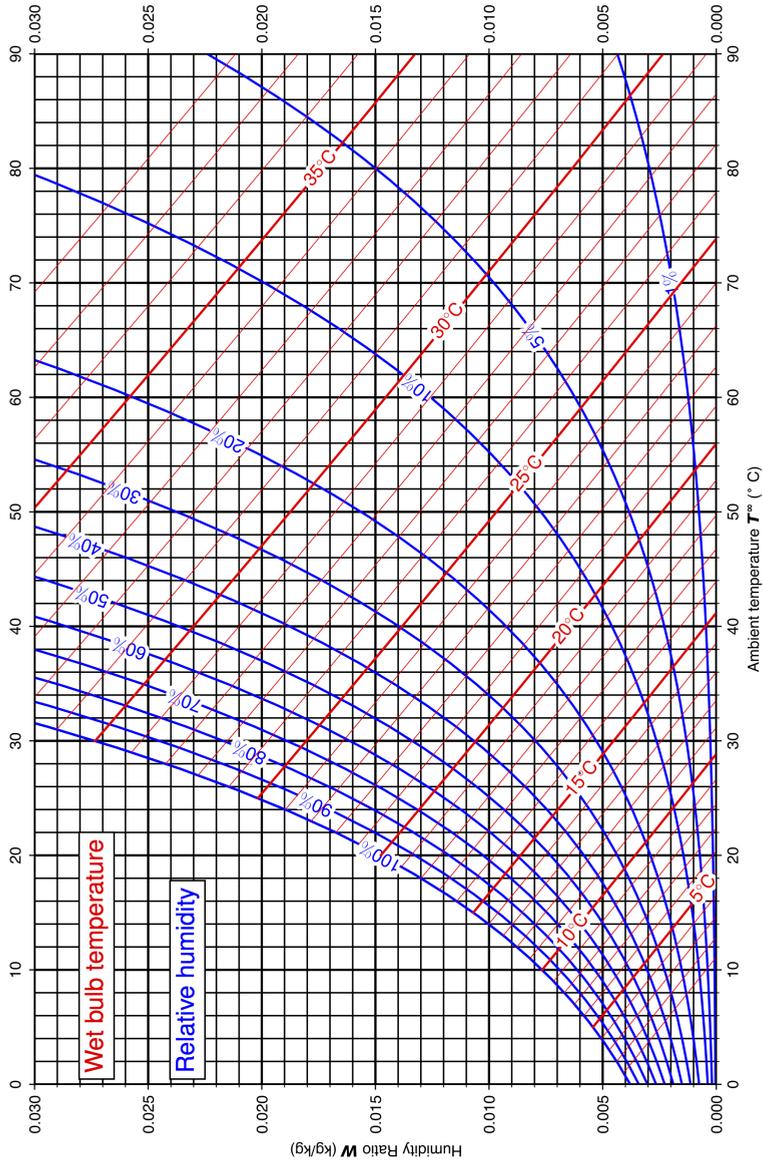
Name	$T$ (°C)	$\rho$ (kg/m <sup>3</sup> )	$C_p$ (J/(kg.K))	$\lambda$ (W/(m.K))	$a$ (10 <sup>-6</sup> m <sup>2</sup> /s)	$\alpha$ (1/K)	$T_{melt}$ (°C)
Aluminium	20	2700	945	238	93.4	24	660
Austenitic steel	20	7900	470	14.5	3.9	15.6	1350 - 1400
Beryllium	20	1848	1780	180	54.7	12	1287
Bismuth	20	9800	129	8.4	6.6	13.3	271
Bronze	20	8800	377	61.7	18.6	17.8	870 - 950
Cadmium	100	8640	246	94.2	44.3	30	321
Carbon steel	20	7860	483	52	13.7	12	1425 - 1460
Cesium	20	1870	242	35.9	79.3	97	28
Chromium	20	7100	474	88.6	26.3	7	1907
Cobalt	20	8780	427	69.1	18.4	12	1495
Constantan	20	8900	410	22.6	6.19	15	1225 - 1300
Copper	20	8960	385	401	116	16.2	1085
Duralumin	20	2790	912	165	64.8	23	500 - 650
Gallium	20	5910	371	41	18.7	18	29.8
Gold	20	19290	128	310	125	14.2	1064
Indium	20	7280	239	81.8	47	33	157
Iridium	20	22400	133	147	49.3	6.4	2446
Iron	20	7870	456	75	20.9	12	1538
Lead	20	11340	127	35	24.3	28.9	327
Lithium	20	534	3570	85	44.5	46	180.5
pearlitic steel	20	7800	486	10.6	10.6	12.5	1400 - 1450
Magnesium	20	1740	1050	159	87	26	650
Manganese	20	7476	477	7.8	2.2	23.6	1246
Mercury	20	13545	139	8.7	4.6	60.4	-39
Molybdenum	20	10200	272	147	53	5	2623
Nickel	20	8900	450	92	23	13.2	1455
Niobium	20	8570	267	52.3	22.9	7	2477
Palladium	20	11970	242	71.2	24.6	11.8	1554
Platinum	20	21500	133	71.2	24.9	8.9	1768
Plutonium	20	19840	130	6.7	2.6	54	639
Potassium	20	860	760	100	153	83	63.5
Rhenium	20	21020	138	48.1	16.6	6.7	3186
Rhodium	20	12500	246	151	49.1	8	1964
Silver	20	10500	235	429	174	19.3	961.8
Sodium	20	970	1234	130	112	70	97.8
Tantalum	20	16500	142	57.5	24.5	6.5	3017
Thorium	25	11720	118	37	26.7	6.5	1750
Tin	20	7290	221	62.8	39	29	232
Titanium	20	4500	522	21.9	9.32	8.5	1668
Tungsten	20	19000	138	174	66.4	4.5	3422
Uranium	500	18600	174	30	9.26	13.4	1132
Vanadium	50	6120	498	31	10.2	8	1910
Wood's metal	20	9730	147	12.8	8.96	20	70 - 80
Zinc	20	7130	385	113	41.2	30	419.5
Zirconium	70	6500	290	22.7	12	5.7	1855

## other solid materials

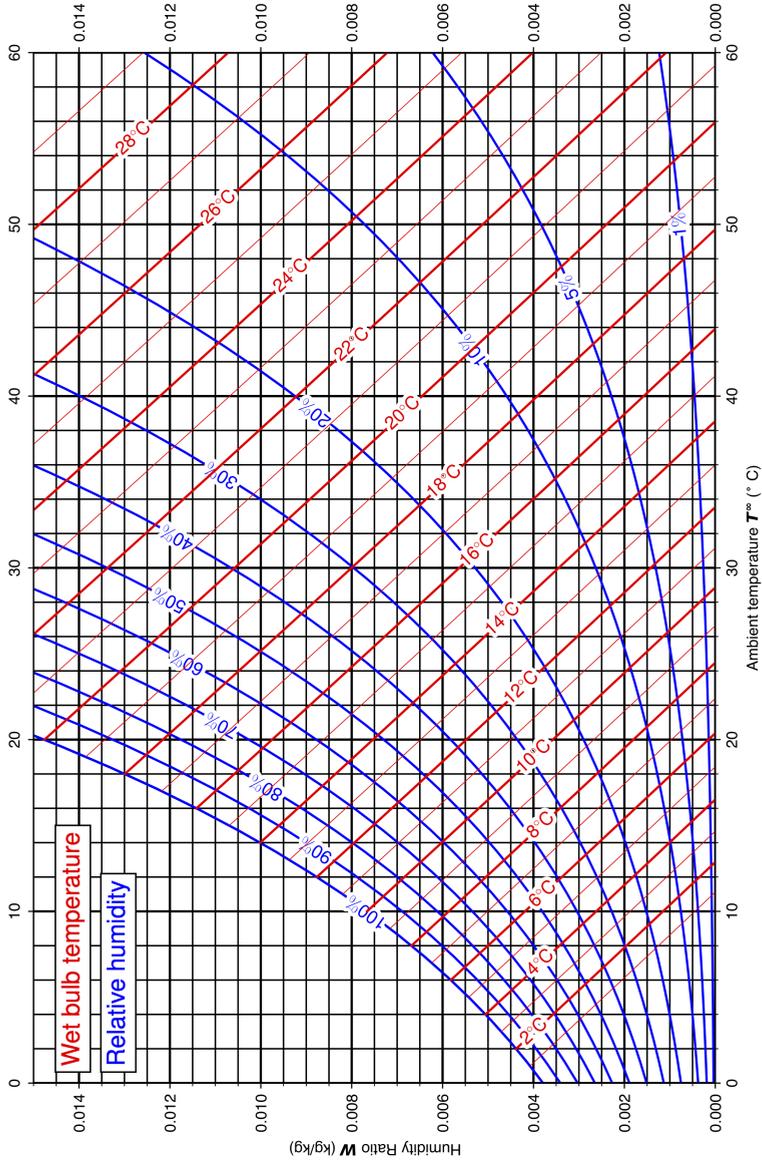
Name	T (°C)	$\rho$ (kg/m <sup>3</sup> )	$C_p$ (J/(kg.K))	$\lambda$ (W/(m.K))	$a$ (10 <sup>-6</sup> m <sup>2</sup> /s)
Asbestos cardboard	20	900	816	0.16	0.22
Asbestos fiber	50	470	820	0.11	0.29
Asphalt	20	2120	-	0.7	0.19
Bakelite	20	1270	1590	0.23	0.114
Cement	20	1900	1130	0.3	0.14
Cement mortar	20	1900	800	0.93	0.61
Chalk stone	20	2000	880	0.93	0.53
Coal (brown)	20	1200	1260	0.26	0.18
Concrete	20	2200	879	1.28	0.66
Cotton	30	80	1150	0.059	0.63
Glass-wool	0	200	660	0.037	0.28
Granite	20	2750	890	2.9	1.2
Graphite (natural)	20	1700	710	100	0.83
Ground (compact)	20	1900	1150	1.5	0.69
Ice	0	917	2040	2.25	1.2
Laminated cloth	20	1350	1500	0.28	1.38
Lead glass	20	2890	680	0.8	0.4
Lime-sand brick	20	1900	840	0.81	0.51
Mineral wool	50	200	920	0.046	0.25
Paper	20	700	1200	0.12	0.14
Paper laminate	25	1350	1420	0.23	0.12
Paraffin	30	925	2260	0.27	0.13
Polyethylene	25	930	2500	0.28	0.12
Polystyrene	20	1050	1250	0.14	0.107
Polyurethane	20	1200	2090	0.32	0.128
Polyvinyl chloride	20	1380	960	0.15	0.113
Porcelain ware	25	2200	900	1	0.5
Quartz	20	2500	780	1.4	0.72
Quartz glass	20	2210	730	1.4	0.87
Red brick	20	1800	890	0.77	0.49
Reinforced concrete	20	2200	840	1.5	0.81
Sand	20	1500	1020	0.5	0.33
Slag concrete	0	1500	750	0.87	0.77
Slag-wool	25	200	800	0.05	0.31
Snow (dense)	0	350	2100	0.35	0.48
Snow (recent)	0	200	2100	0.1	0.24
Sponge rubber	20	250	2050	0.06	0.12
Sulfur	20	2070	720	0.27	0.18
White rubber	20	1100	1670	0.16-0.23	0.087-0.095
Window glass	20	2480	800	1.16	0.58
Wood (pine)	20	550	2700	0.16	0.1

# Mollier Diagrams

## Large range



# Detailed range



# Other

## Physical constants

Name	Symbol	Value	Unit
Gas constant	$R$	8.314463	$J/(mol.K)$
Avogadro number	$N_A$	$6.022045 \times 10^{23}$	$mol^{-1}$
Gravitational acceleration	$g$	9.81	$m/s^2$
Stefan Boltzmann constant	$\sigma$	$5.67032 \times 10^{-8}$	$W/(m^2K^4)$
Boltzmann constant	$k$	$1.380662 \times 10^{-23}$	$J/K$

## Unit conversions

Examples:  $10^5 Pa = 10^5 \div 6.89 \times 10^3 = 14.5 psi$ ,  $77 ^\circ F = 77 \div 1.8 + 255.37 = 298.15 K$

Symbol	Quantity	Unit	→	Conversion	←	SI units
$p$	Pressure	$psi$	$\times$	$6.89 \times 10^3$	$\div$	$Pa$ or $N/m^2$
		$atm$	$\times$	$1.1013 \times 10^5$	$\div$	
		$bar$	$\times$	$10^5$	$\div$	
		$mm Hg$	$\times$	$1.33 \times 10^2$	$\div$	
$\mu$	Dynamic viscosity	$cP$	$\times$	$10^{-3}$	$\div$	$Pa.s$
$T$	Temperature	$^\circ C$	$+$	273.15	$-$	$K$
		$^\circ F$	$\div 1.8 + A$	$A = 255.37$	$\times 1.8 + B$	
$Q$	Power	$hp$	$\times$	745.7	$\div$	$W, J/s$ or $kg.m^2/s^3$
$F$	Force	$lbf$	$\times$	4,44822	$\div$	$N$ or $kg.m/s^2$
$E$	Energy	BTU	$\times$	$1.0551 \times 10^3$	$\div$	$J$ or $kg.m^2/s^2$
		$cal$	$\times$	4.184	$\div$	



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# References

The majority of the information presented in this reference book consists of very general knowledge. Some information, however, is more specific and can be attributed to the references provided below.

The following sections use data from: *Handbook of hydraulic resistance*, I.E. Idel'chik, Israel Program for Scientific Translations Ltd. (1966):

- page 10 **sharp and smooth bends** ( $Re > 3 \times 10^5$ )
- page 11 **sudden expansion and contraction**
- page 12 **sharp-edged orifices (thickness  $< 1.5\%$  of  $D_h$ )**
- page 14 **diffusers and contractions** ( $Re \equiv w_0 D_h / \nu > 10^4$ )
- page 15 **circular or square pipe entrances and exits**

The following sections use formulas as proposed in: *Energy losses at 90° pipe junctions*, Itō, H. and Imai, K., *Journal of the Hydraulics Division*, vol. 99, pages 1353–1368 (1973):

- page 13 **converging and diverging T-junctions** ( $Re \equiv w_3 D / \nu > 10^5$ )

The following sections contain fluid and gas properties calculated by the CoolProp library ([www.coolprop.org](http://www.coolprop.org)). Details of this library can be found in *Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp*, Bell, I. H., Wronski, J., Quoilin, S. and Lemort, V., *Industrial & Engineering Chemistry Research*, vol. 53, pages 2498–2508 (2014)

- page 27 **water at  $p = 10^5$  Pa**
- page 28 **air at  $p = 10^5$  Pa**
- page 29 **other fluids and gases at  $p = 10^5$  Pa,  $T = 20$  °C**
- page 37 **Mollier Diagrams**

The following sections are taken from the following sources:

- page 40 **Periodic table of chemical elements** By Ivan Griffin (2009-2010)

# Graphs, Formulas and Tables relevant to Transport Phenomena

## 2nd edition

Martin Rohde

This book provides relevant information required during BSc-level courses on Transport Phenomena, encompassing micro- and macroscopic balances, correlations for friction, heat transfer and species transport and material properties. The information comes in handy during exercise classes and written exams.



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